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An EHF and laser intersatellite communication link comparison and selection methodology

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AN EHF AND LASER INTERSATELLITE COMMUNICATION LINK COMPARISON AND SELECTION METHODOLOGY

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THESIS

AN EHF AND LASER INTERSATELLITE COMMUNICATION LINK COMPARISON AND SELECTION METHODOLOGY

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Present and future communication requirements establish the need for a high data rate satellite to satellite trunking system. The advent of the CW laser systems and transmitting sources at 60 GHz offer a "new" and wide electromagnetic spectrum for use in space telecommunications. The fundamental objective of this study is to provide the systems designer and the communication system user with reference data,

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An EHF and Laser Intersatellite Communication
Link Comparison and Selection Methodology

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ABSTRACT

Present and future communication requirements establish the need for a high data rate satellite to satellite trunking system. The advent of the CW laser systems and transmitting sources at 60 GHz offer a "new" and wide electromagnetic spectrum for use in space telecommunications. The fundamental objective of this study is to provide the systems designer and the communication system user with reference data, supplemental data, and a trade-off methodology for selecting the system (EHF or laser) which best suits their requirements. Special treatment is given to the determination of signal-to-noise ratios in the evaluation of optical and millimeter wave heterodyne systems.

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I. INTRODUCTION

A. STATEMENT OF INTENT

There is foreseen a future need for synchronous satellite trunking utilizing the technology of an optical laser system or an EHF RF system to fulfill anticipated high data rate communication requirements.

It is the purpose of this thesis to present and justify the background information for this anticipated need, discuss the expected frequency selections for the two proposed systems, and describe the systems.

A comparison of the two systems will be made based on the performance parameters which determine the signal-to-noise ratio, the shortcomings of each system, and the future expectations for each technology.

A discussion will also be presented on the optimization of system burdens of cost, weight, and power, based on the performance parameters. It will include the development of a cost/unit channel capacity factor that can be used as a selection criterion between similar systems or systems with contrasting technologies.

B. EHF AND LASER COMMUNICATIONS

With the ever increasing volume of information to be passed, the telecommunications industry, civilian and military, has searched for higher and higher channel capacity and consequently higher and higher carrier frequencies to

transport this information. Although to date, the bulk of all communications has been below 10 GHz, this portion of the spectrum is rapidly becoming overcrowded with a resulting increase of interference problems. Present telecommunications systems, especially satellite systems, are requiring more and more bandwidth to handle increased data rates particularity with the shift from analog to digital communications. A second related pressure being applied to the spectrum below 10 GHz is the ever expanding communication requirements and capabilities of the lesser developed countries of the world. These countries are becoming aware that the frequency spectrum is a national asset resulting in increased competition for the available spectrum. Undoubtedly the result will be tighter controls being placed on the RF spectrum and increased difficulty in obtaining additional allocations. Such pressures on the conventional RF spectrum are driving the telecommunications industry to exploit new regions of the electromagnetic spectrum. The new regions are millimeter waves (30-300 GHz) and optical frequencies (10^{13}-10^{15} Hz). Both of these regions have the primary advantage of immense instantaneous bandwidths. The EHF portion of the spectrum contains approximately 10 times the available bandwidth of all RF and microwave frequencies while optical frequencies offer approximately 20,000 times the bandwidth of the total RF spectrum including the EHF portion. These large bandwidths permit high information rates and/or the use of sophisticated signal processing techniques to provide protection against electronic countermeasures.

In addition, high-gain, high-resolution antennas, narrow beamwidths, and compact component size offer significant advantages for telecommunications. For military applications, narrowbeam, high-gain antennas at these frequencies will allow secure communications by reducing the effective intercept and jamming areas available to enemy forces.

C. COMMUNICATION LINK OF INTEREST

There are four types of links that have been proposed for the evolving EHF and laser technologies in the field of satellite communications. These links include: (1) ground terminal to synchronous satellite, (2) synchronous satellite to ground terminal, (3) low-altitude satellite to synchronous satellite, and (4) synchronous satellite to synchronous satellite. In the mid-1960's, EHF and laser links involving a ground terminal and a synchronous satellite attracted the attention of design engineers and communication system users as possible alternatives to the space microwave systems being implemented (e.g., Communication Satellite Corporation's INTELSAT). The rapid advancement of space technology resulting from the "race to the moon" served as the impetus for proposing the low-altitude satellite to synchronous satellite and the synchronous satellite to synchronous satellite links as additional utilizations of the concurrently advancing EHF and laser technologies. Sophisticated applications such as data relay satellites were proposed by Goddard Space Flight Center and the Jet Propulsion Laboratory. These satellites would be stationed in geosynchronous orbit and would receive

the information collected by low-flying satellites and relay this information, at high speeds, to another synchronous satellite or perhaps to a ground terminal. This kind of satellite relay system would obviate the necessity for the extensive network of NASA's ground stations around the world and result in considerable cost savings.

COMSAT Corporation is also planning a satellite to satellite communication link for transmission of the ever increasing load of international commercial traffic as an alternative to its present system.

D. MILITARY SYNCHRONOUS SATELLITE APPLICATION

The military has foreseen a utilization for such a synchronous to synchronous satellite relay system. With the ever-increasing number of reconnaissance, surveillance, and early warning satellites, a data relay system would allow longer missions for the low-altitude satellites because their film carrying capacity would no longer be the limiting factor in satellite lifetimes. In addition, this system for data relay between synchronous satellites would allow more evaluation and response time for the critical information received from the early warning satellite system. The lag time for the low-altitude satellite to pass over friendly territory to drop its film or transmit its information would be eliminated. This system of satellites could also be used to allow for more rapid communication of normal operational and administrative message traffic with fewer expensive ground terminals.

E. THE SYNCHRONOUS SATELLITE LINK AT 30 MHz BANDWIDTH - A SYSTEMS COMPARISON BASE

The synchronous satellite to synchronous satellite link is specified as the basis for comparing EHF and laser systems. For this application the EHF and laser systems must be wide-band; therefore, a requirement of 30 MHz has been imposed upon these systems for the purpose of comparison.

Both EHF and laser systems are capable of larger modulation bandwidths; however, for this paper FM modulation has been selected. The 30 MHz restriction is due largely to the fact that FM intracavity modulation of the CO_2 laser is limited to the rotational-vibrational linewidth which is in the order of 30 MHz. This bandwidth restriction does not unduly limit this discussion because it is sufficient to handle the data output of most proposed applications. For instance, the Earth Resources Technology Satellite (ERTS) has a data output of one 3.5 MHz video channel and one 15 Mbit data channel, both of which can easily be handled by 30 MHz bandwidth. In fact, seven 3.5 MHz video channels could simultaneously be transmitted with this bandwidth. Heterodyne detection is proposed for this comparison because it is superior to direct envelope detection in sensitivity and ability to discriminate against background noise at 10.6 μm. Also at EHF frequencies, the heterodyne technique involves less equipment complexity than that required by other detection schemes at this bandwidth.

The link discussed here consists of a half-duplex link between two satellites in geosynchronous orbit stationed in two of the three trisatellite-system positions 73,000 km apart. Transmission and reception of information to a third synchronous satellite, low-altitude satellite, or ground terminal have been excluded from this discussion.

II. LASER SYSTEM DESCRIPTION

A. LASER SOURCE SELECTION (CO_2 vs Nd:YAG)

An imposing number of coherent optical sources have been demonstrated with useful power outputs at wavelengths which span the entire optical spectrum. Lasers of all types (solid-state, semiconductor, liquid, and gas) both pulsed and continuous have been utilized to investigate specific optical communication problems but only a few have received the serious attention and development necessary to realize performance as practical optical communication sources. Reference 1 states that in selecting a source, those characteristics most important for communications are: (1) power output, (2) lifetime, (3) efficiency, (4) mode control, (5) frequency control, and (6) growth potential. A survey of present laser system candidates for wideband space communication quickly converges on two choices upon analysis of these parameters. These systems are the carbon dioxide (CO_2) laser operating at 10.6 μm and the neodymium: yttrium aluminum garnet (Nd:YAG) laser operating at 1.06 μm or alternatively doubled to 0.53 μm.

According to Ref. 2 the minimum output power that is deemed necessary to deploy a practical laser communications system is 0.2 W in order to avoid using extremely narrow beamwidths. Also the prime input power limit for the transmitting source should be 100 W because this is the maximum that is assumed compatible with conventional communication satellites.

To date no Nd:YAG source has attained this level of output power within the limit of 100 watts of pumping power. Reference 3 however reported a 1 W output obtained with 230 watts of input from a potassium-rubidium (K-Rb) lamp with a water-cooled rod. More recently an output power of 1.7 watts was attained with a pumping power of 800 watts [Ref. 4]. The most efficient performance of Nd:YAG laser in the 1-15 watt range is 1% using the tungsten-iodide (W-I) pump lamp. By contrast CO_2 lasers have operated to 30% efficiency at high output powers with 20% being routinely accomplished. For the size of laser which delivers one to several watts, 10% efficiency is readily achievable [Ref. 2]. With the use of modulation, the efficiency may drop to 1-3% but still effectively meets the 100 W maximum transmitter prime power limit.

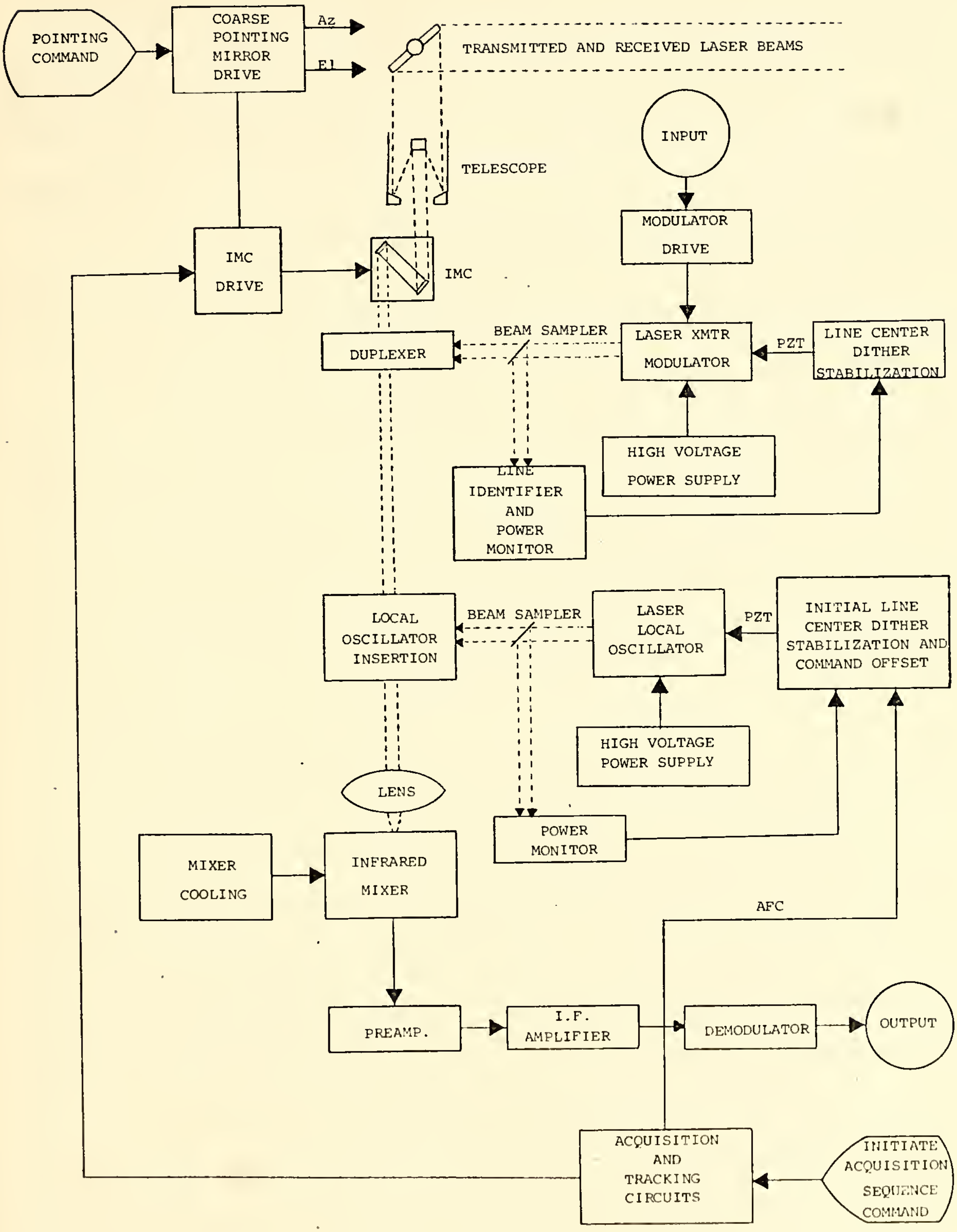
The operational lifetime of the Nd:YAG laser is generally determined by pump life and the life of ancillary equipment. For W-I lamps operating at a filament temperature of $3400^{o}K$, lamp life is typically 200 hours. Lamps designed for $3000^{o}K$ operation have a rated life of typically 2000 hours [Ref. 1]. Newer pump sources such as light-emitting diodes offer much promise for application to the Nd:YAG laser, but at present have exhibited short lifetimes measured in tens of hours. Lamp life is one of the major obstacles to be overcome for an effective Nd:YAG system. CO_2 laser lifetimes are somewhat better with sealed-off CO_2 discharge tubes exhibiting lifetimes in excess of 10,000 hours. Reference 5 recently reported a 1 watt sealed-off CO_2 laser using a gas volume of

50 cm^3 that had an initial output of 0.72 W which rose to 1.1 W after 3000 hours and still gave 0.7 W after 12,000 hours of operation using an internally oxizided silver-copper alloy cold cathode. Lifetimes are increasing rapidly with advancing knowledge of discharge chemistry.

Multimode output is typical for Nd:YAG lasers but in order to attain diffraction-limited efficiency, the lowest order transverse or TEM_{oo} mode of operation is desired. Introduction of mode control techniques may cause a degradation of power by as much as one half. Similarly frequency control lowers output power. By employing a birefringent etalon to provide both axial-mode selection and a frequency discriminant, a stabilized single frequency laser has been operated with frequency fluctuations of less than 2% with the power output reduced to 40% of the multimode power [Ref. 1]. Frequency doubling and simultaneous mode locking will reduce the efficiency of the Nd:YAG laser still further. For the CO_2 laser source, operation in the lowest transverse mode is relatively easily obtained by sufficiently restricting the diameter of the resonator at some point with an aperture stop. Likewise stable single frequency operation has been demonstrated by Mocker [Ref. 6]. The results of his system indicated that in the free-running case, a short-term stability (1/10 sec.) of 1 part in 10^{10} (3 KHz) and a long term stability (20 min.) of 1 part in 10^8 has been achieved with a rigid cavity design without employing any feedback techniques. An AFC loop locks the laser in frequency with an accuracy approaching 1 part in 10^{11}.

At present the CO_2 laser seems to have the greatest growth potential for an eventual role in near-earth satellite communication. However, it is too early at present to preempt options to choose either a 0.53 μm or 10.6 μm system approach because both require performance increments and innovations. The conclusion drawn is that at present it appears that the best laser for optical space would be a small, efficient, lightweight 10.6 μm CO_2 laser in a spacecraft with coherent detection (superheterodyne).

B. SYSTEM DIAGRAM [Ref. 8]



C. COMPONENT DESCRIPTION

The satellite flight package consists of five parts:

(1) The optical subsystem contains a course beam-pointing mechanism (slewing mirror), a 5-inch Cassegrainian telescope, image-motion compensator (IMC), directive mirrors, and beam splitters.

(2) The laser subsystem contains the 2 watt laser transmitter and modulator, the 200 mW laser local oscillator (LO), the frequency-stabilization servo, and laser power meters.

(3) The detector subsystem contains the signal information detector, detector preamplifiers, image-motion detector, and radiation cooler.

(4) The signal-processing subsystem contains the intermediate frequency (IF) post amplifier, image-motion compensator drive electronics, and laser transmitter modulator drive electronics.

1. Optical Subsystem

The optical subsystem is designed to scan the transmitted beam and receiver over the required field-of-view, form a narrow transmitted beam, collect energy in the infrared portion of the spectrum, divide it between image-motion sensor and information detector, and superimpose local oscillator and received radiation to produce heterodyne action.

a. Coarse Beam-Pointing Mechanism

The mechanism serves to direct the transmitted modulated beam toward a second equatorial satellite position as well as to direct the received laser signal into the

Cassegrainian telescope. To position the mirror within the ±0.1-degree satellite-stabilization uncertainty, a 50-position resolver is required in the north-south, or Y-axis, direction and a 300-position resolver in the east-west, or X-axis, direction. After acquisition, corrections to the beam direction will be accompolished by a fine-control mechanism; therefore, very little repetitive positional movement is required of the course beam-pointing mechanism. The coarse-pointing mechanism is a lightweight mirror of beryllium overcoated with 0.006 inch of Kanegen before optical polishing. Metal mirrors are especially attractive because of their lightweight, ease of mounting, high modulus of elasticity, and favorable thermal properties [Ref. 7]. For 10.6-micron wavelength, the mirror flatness is not seriously degraded in the expected space environment, and can be easily achieved.

b. Telescope

The telescope (optical antenna) required is a 5-inch aperture system with a 0.2-degree field-of-view. It acts much in the manner of an RF antenna; that is, it focuses the laser output into a high power-density beam during transmission and provides maximum power-gathering area during reception. The telescope is composed entirely of reflective beryllium mirrors. After optical polishing, the mirrors are coated with vacuum-deposited aluminum to provide a reflectance as high as 98% at 10.6-micron wavelength. Special paints and baffles used in the telescope and telescope housing will reduce scattered light and provide temperature control.

c. Image-Motion Compensator

After the telescope collects and focuses the received energy, the energy passes through a negative lens that also acts as a filter. This negative lens collimates the converging telescope rays into a pencil-thin parallel beam which is then directed into the image-motion compensator, or fine-pointing mechanism. This consists of a pair of mirrors mounted on piezoelectric elements which steer the incoming and outgoing laser beams in two directions [Ref. 8]. The IMC corrects instabilities in satellite pointing. The satellite will be earth-oriented and stabilized by a 3-axis inertial-wheel control system to a specified accuracy of ±0.1-degree, with a jitter rate of 0.0003 degrees per second. The required pointing accuracy of the optical system is approximately ±0.003 degree, representing a dynamic control range requirement of only 36:1 [Ref. 7]. The technique used for optical beam steering is based on small piezoelectric bender bimorphs as the active deflection elements. By moving one mirror in a direction orthogonal to the movement of the other mirror, and infinite number of beam directions may be obtained to within the resolution of the system.

2. Laser Subsystem

This subsystem is composed of a 2-W transmitter laser, an electro-optic intracavity modulator assembly, a 200 mW local oscillator, and the frequency-stabilization and tuning mechanisms, required for heterodyne operation.

a. Transmitter Laser

The laser discharge tube is a sealed-off tube constructed of the low thermal expansion material, Cervit, with a bore diameter of 5 mm, bore length of 35 cm including Brewster windows, and an overall resonator cavity length of 45 cm. A length of approximately 10 cm is available between the discharge tube and the output mirror for mounting the electro-optic modulator crystal. The cathode is of internally oxidized silver-copper alloy construction to obtain maximum lifetime (12,000 hours) from the single-fill discharge tube [Ref. 5]. The length of the laser cavity changes with changing temperature. Therefore low expansion material is used to minimize this drift so that the cavity length stays within the range of the length control servo-system. This active frequency-control element reduces the thermal control requirement. The housings for the transceivers consist of built-up channel structures which act as optical benches to maintain optical alignment. The laser tube is clamped in a high conductance mount to provide a path for the heat to be transferred to the radiation cooler where it is radiated to space. Laser oscillators are inherently capable of very high spectral purity, but their performance is degraded by acoustical and mechanical vibration. Isolation from both acoustic and mechanical interference has been increased by designing the laser cavity to have a high mechanical resonant frequency. This is achieved by constructing the cavity from tubular material with large area contacts

between all parts and by rigid clamping of parts. The cavity then tends to move as a unit reducing the frequency modulation effect. [Ref. 9].

b. Laser Local Oscillator

This laser is essentially identical to the transmitter laser with the exception that the local oscillator resonator cavity does not contain an electro-optic modulator crystal. This laser is constructed of the same materials using the same construction techniques. The physical size has been scaled down to provide only 200 mW of output power, since this is all that is required for the heterodyne process and, in fact, additional power might burn out the detector. In addition to the tuning and frequency-stabilization circuitry, the laser local oscillator has the automatic frequency control circuitry necessary to track the transmitter laser frequency.

c. Modulator Assembly

This system utilizes intracavity electro-optic modulation with an FM format. The cadmium telluride (CdTe) modulator used is rectangular parallelepiped single crystal with the following dimensions and crystal orientation: 5 mm in width in the (001) direction, 5 mm high in the (110) direction,and 40 mm in length in the (110) [Ref. 10]. The crystal becomes birefringent when an electric field is applied along the (110) direction. The two ends are parallel polished flat and antireflection coated to yield no more than a maximum reflectance of 3 percent at 10.6-μm wavelength.

The modulator is soldered directly to gold-plated lead electrodes used for acoustic damping, then mounted between beryllium oxide (BeO) supports for high thermal conductivity. Heaters and a temperature sensor are incorporated to form a regulated oven for temperature control. The entire unit is mounted inside a fiberglass sleeve for thermal isolation, then installed in an aluminum mounting fixture and placed in the resonator cavity [Ref. 9].

d. Tuning and Frequency-Stabilization Servo

For a heterodyne communication system, both the transmitter and local oscillator laser must oscillate on the same transition of the rotation-vibration band of carbon dioxide. To have the same specified transition (i.e., P-20) oscillate in both lasers, a frequency tuning capability is required for each laser. Both the long-term stability and resettability must be within a fraction of the doppler width (±25 MHz) [Ref. 6]. Transition selection and fine frequency control are achieved by controlling the voltage applied to piezoelectric transducers attached to the resonator cavity output mirror. This is accompolished by sampling the energy leaving the end mirror of the transmitting laser with a partially reflecting beamsplitter used in front of a power monitor. The laser cavity is swept until an output is obtained from the power monitor thus stopping the sweeping process. A dc voltage is then applied to the piezoelectric tuner and held. This process tunes the transmitter laser to within nominally 50 MHz of the desired operating frequency.

Line-center dither stabilization is then used to stabilize the transmitter laser to the peak of its gain curve and therefore within a few kilohertz of the desired frequency for the duration of the operating period. The tuning and frequency-stabilization of the local oscillator laser is identical to the transmitter laser except that the local oscillator employs a diffraction grating as one of its laser mirrors. After the tuning and stabilization process is completed, a precise dc voltage is applied to the piezoelectric tuner and the line center dither is disengaged. This dc voltage varies the laser cavity length by a fixed amount and therefore tunes the local oscillator to a fixed offset frequency. This offset determines the intermediate frequency of the receiver, because the other transmitter laser is line-center dither stabilized to the peak of the same vibrational-rotational transition. Automatic frequency control (AFC) operation is conventional with the AFC error signal derived from the dc coupled output of the limiter-discriminator following the signal IF amplifier. The AFC signal is applied to the line-center dither stabilization unit, completing the AFC loop.

3. <u>Detector Subsystem</u>

a. Signal Information Detector

The optical subsystem directs the incoming infrared signal information to the signal information detector. Coherent heterodyne detection is proposed because it is superior by six orders of magnitude to direct envelope

detection in sensitivity and ability to discriminate against background. Heterodyne detection involves the coherent mixing of the incoming laser signal with the local oscillator at the detector, which has a square law response. The ultimate sensitivity limit for heterodyne detection, termed the quantum limit, is 2 $h\nu\Delta f$ or, nominally, 10^{-20} watts per cycle of bandwidth. Sensitivities within a factor of 2 of the quantum limit are attainable. The detector used is a sensitive wideband mercury cadmium telluride (HgCdTe) detector of 10.6-micron energy, which can be operated at temperatures well above that of liquid nitrogen (77°K). The possibility of obtaining satisfactory performance at increased temperatures, up to 100°K, allows the use of radiation coolers that require no power from the satellite's power supply, and have very low weight and an extremely long operating lifetimes. The effect of operating temperature on detectivity of a HgCdTe has been reported by Ref. 7 which showed that a detector having a detectivity (D*) of 4.5×10^{10} cm $Hz^{\frac{1}{2}}$/watt at 77°K will have a D* of nominally 3.5×10^{10} cm $Hz^{\frac{1}{2}}$/watt at 100°K, and 5.0×10^{9} cm $Hz^{\frac{1}{2}}$/watt at 130°K.

b. Fine Beam-Pointing Error Sensor

The fine beam-pointing error sensor provides the servo signals necessary to operate the image-motion compensator that controls the direction of transmitted and received rays. Sensor operation can be divided into two modes: acquisition and tracking. The acquisition mode starts when the image-motion compensator initiates a scan

program; it terminates when the error sensor registers acquisition of received radiation and sends a command to the scan program to halt the scanning operation. The tracking mode starts with the acquisition of a signal. After acquisition has been registered, the image of the incoming laser beam is automatically centered on the sensor. Subsequent drifts in the image position result in azimuth and elevation error voltages that cause the image-motion compensator to recenter the image. As in the signal information detector, heterodyne detection will be used for maximum sensitivity. HgCdTe detectors will be used because of their excellent performance at temperatures near 100°K. The beam-pointing error sensor consists of four detectors. Each detector is followed by an identical sequence of preamplifier, filter, and RF detector. The optical system that directs the received laser energy to the signal detector also supplies the signal to the error sensor. A 2 by 2 array is employed in conjunction with a scanning system that uses the image-motion compensator. The scanning programmer causes the image-motion compensator to begin a rectangular raster scan covering the 0.2-degree field. The dwelling time at each position is in accordance with the tracking bandwidth. The dwelling time is also long enough to permit acquisition when the beam strikes one detector element. The design results in typical acquisition times of much less than 1 minute. After acquisition, a scan stop command is sent to the scanning programmer, which halts and locks the scan of the image

motion compensator to center the image on the sensor. Henceforth, imbalances in the power reaching the four detectors produce azimuth and elevation error voltages that direct the image-motion compensator to reposition the image.

c. Radiation Cooler

Maintaining the five HgCdTe detectors below $100^{\circ}K$ with a passive radiator represents the limiting problem thermally. In order to maintain temperatures below $100^{\circ}K$, the radiator must be extremely well insulated from the vehicle, and can receive no direct or reflected solar energy. This vehicle insulation problem can be solved by a staged radiator system consisting of a number of circular discs with decreasing diameters, which are insulated from one another. The detector is mounted to the outer disc, which is sized to reject the detector dissipation plus the heat leak from the preceeding disc. The area on the outer surface of each disc from the outside diameter to the diameter of the subsequent disc has a high emissivity, allowing the heat leak from the vehicle to the first disc to radiate from the extended disc area. Consequently, temperature of the first disc is reduced and the heat leak to the next disc is minimized. With no other external fluxes incident on this staged radiator system, the outer detector stage will have a radius of 3 inches at $77^{\circ}K$; four other stages with temperatures of about $87^{\circ}K$, $113^{\circ}K$, $158^{\circ}K$, and $198^{\circ}K$ will insulate the detector sufficiently from a $294^{\circ}K$ vehicle [Ref. 7]. In addition, a shield system is required to protect the entire staged radiator

system from external fluxes. With a radiation capability of 0.53 watts/ft^2 at 100°K, a detector temperature level between 77°K and 100°K will result.

4. <u>Signal Processing Subsystem</u>

This subsystem, consisting of the intermediate frequency post amplifier, image-motion compensator drive electronics, and laser transmitter modulator drive electronics, will not be discussed here because the attendant technology has been well defined and described in conventional communication applications.

III. MILLIMETER WAVE SYSTEM DESCRIPTION

A. EHF ADVANTAGES FOR A SATELLITE CROSSLINK

For the synchronous to synchronous satellite communication link, utilization of a millimeter wave band in the EHF region (30-300 GHz) of the RF spectrum is a viable alternative to the foregoing proposed optical system [Ref. 11]. For the millimeter link, as with the laser system, the potentials include high data rate broadband information transfer applications such as high speed digital data and multichannel voice links via satellite trunking. It is anticipated that a future generation "Intelsat" trunking network between satellites will be the first implementation for civilian or military use. This will significantly relieve the ever increasing crowding in the lower portions of the RF spectrum [Ref. 12].

As with the laser system, high gain with attendant narrow beamwidths from reasonably small satellite antennas can be achieved at a millimeter wave frequency band [Ref. 11]. The inherent compactness of the RF components at these short wave lengths reduces the equipment size and is especially useful in obtaining physically small antenna structures [Ref. 13]. Between two fixed size antennas separated by a fixed distance in space the link gain increases as the square of the operating frequency. This indicates the desirability of increasing the intersatallite link frequency to as high a value as possible, consistent with state of the art system hardware capabilities [Ref. 14].

The EHF portion of the radio frequency spectrum is ideal for space to space satellite communications since it is generally unsuitable for conventional terrestrial communication links (except for very short range tactical applications - see Ref. 15) because of excessive attenuation in the troposphere [Ref. 16]. It has been shown in previous studies that this absorption can be a highly reliable mechanism to achieve protection against electronic countermeasures for the satellite to satellite link.

B. THE EHF 60 GHz FREQUENCY CHOICE

Although the atmosphere absorbs electromagnetic energy at all frequencies, the magnitude of this absorption is insignificant until the frequency is well within the microwave region. As the frequency approaches what is called molecular resonance of one of the atmospheric constituents, the absorption becomes substantial. A number of these molecular resonances fall within the millimeter region, producing absorption peaks at 22, 60, 118, 184 and 324 GHz. The peaks at 22, 184 and 324 GHz are due to water vapor with the attenuation peaks at 60 and 118 GHz due to oxygen absorption [Ref. 13].

The World Administrative Radio Conference on Space Telecommunications, which met in Geneva in 1971 to act on proposed and recommended frequency allocations, specified the frequency band from 59.0-64.0 GHz for space to space communications [Ref. 12].

With the maximum atmospheric attenuation at 60 GHz, which is within the specified range, this discrete band represents the best choice as a satellite link. It is also the highest absorption band achievable for the sake of maximum antenna gain since 118 GHz is above what is considered to be the current state of the art ceiling of 100 GHz for certain hardware components [Ref. 17]. As well as providing a high degree of shielding against interference from ground stations and high altitude aircraft, the 60 GHz carrier frequency region is very desirable from the standpoint of maximizing link information capacity. When considering current or expected noise-figure and RF-loss factors, the information bandwidth to RF power ratio maximizes in the 60 GHz region [Ref. 18]. For these reasons the 59.0-64.0 GHz band was allocated for space to space communications and 60 GHz is specified for this intersatellite application.

C. HARDWARE REVIEW FOR SYSTEM COMPONENT SELECTION

Planning an EHF communication system for an intersatellite link, which will be compared with the laser optical link, consists of a critical review of state-of-the-art hardware for component selection within the framework of the proposed system. Since no actual EHF satellite trunking link has as yet been tested, a candidate system can only be postulated based upon current technology and laboratory tested hardware.

The factors critical to an EHF intersatellite link are: operating bandwidth and frequency; receiver sensitivity;

transmitter output power; antenna pattern, gain, pointing and tracking; and modulation for high speed, half-duplex traffic. Before these critical factors can be quantified for a performance comparison with the proposed optical system the EHF hardware components must be identified. These system peculiar components are: the transmitter package, mixer, local oscillator, modulator, and a light weight, high gain antenna with the necessary acquisition and tracking capability. Components which are basically common to any RF system, in terms of performance specifications, are the IF amplifier and detector [Ref. 15].

A millimeter wave experiment was launched on board the Applications Technology Satellite (ATS-V) in August, 1969, for the purpose of measuring the effects of atmospheric propagation on a satellite to ground link at 15.3 GHz and a ground to satellite link at 31.65 GHz [Ref. 19]. The atmospheric propagation is of course no concern in the inter-satellite space link; however, the experimental spacecraft hardware communication flight package configuration can serve as the basis for postulating a 60 GHz intersatellite link system design.

Where a detailed explanation of the integrated system's operation was necessary to explain feasibility in the case of the foregoing laser/optical system, the conceptual EHF link is presented as a structural component description. The task at hand is to postulate a candidate EHF system by reviewing hardware alternatives in order to establish a

technically plausible system for performance comparison with the laser/optical proposal. Figure 2 represents the component framework for this hardware alternative review.

G. J. Bonelle analyzed the 10-95 GHz range for hardware capability and specified the following key components for identification in the order of their priority [Ref. 16]. These are:

A high gain antenna

A signal source and power amplifier

Solid state frequency upconverters (if required)

A low noise receiver

A solid state local oscillator

This will serve as the basis for the EHF hardware review.

1. <u>EHF System Design Framework Diagram</u>

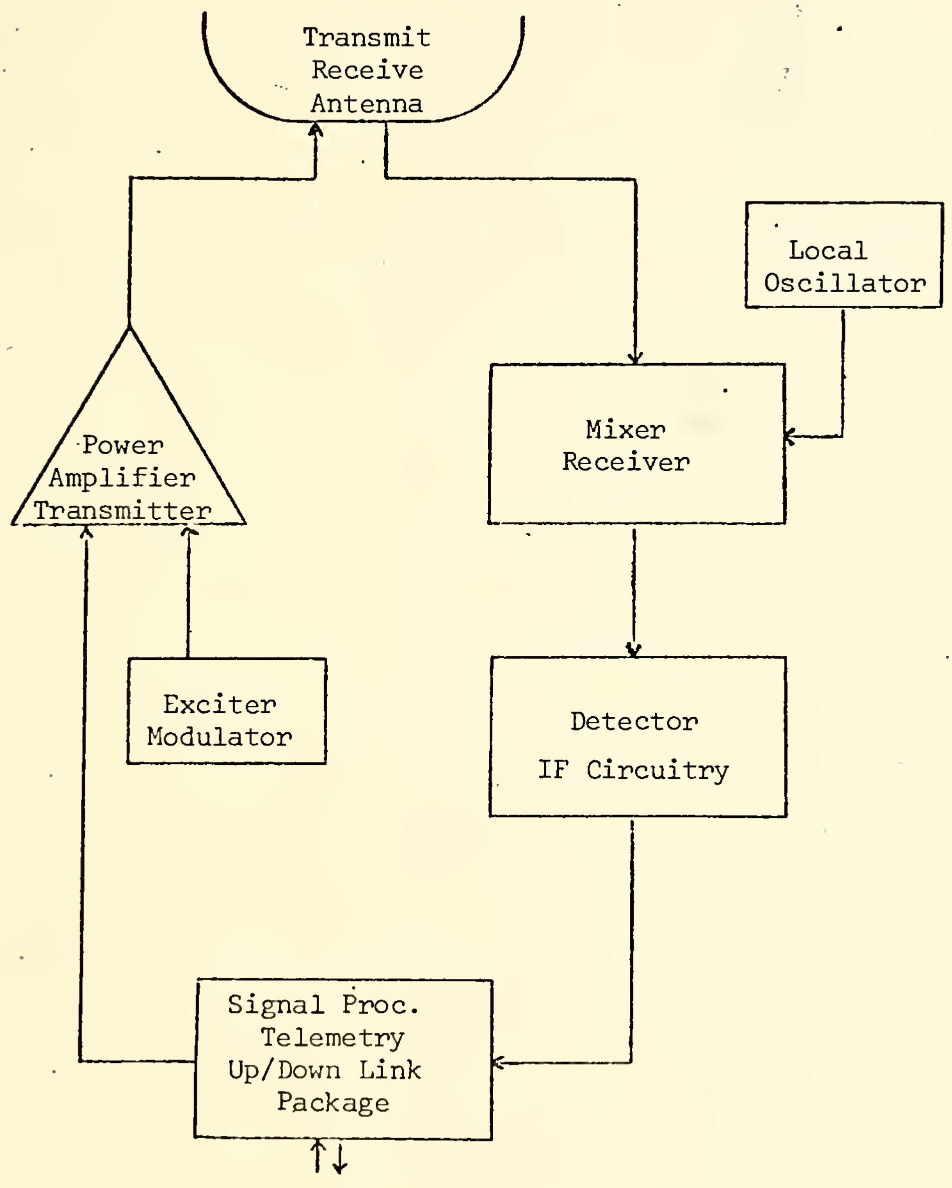


Figure 2

2. Antenna Considerations

All practical antennas are based on geometric optical designs, such as parabolic reflectors, Cassegrain systems, or lenses. At millimeter frequencies, unlike lower bands, the physically small high gain antenna is predominant in all designs. Figure 3 shows the gain and beamwidth vs. reflector diameter of these typical quasi-optical antennas. As developed by A. F. Kay, in his paper on millimeter wave antennas, a trend is shown that for the highest gain antennas practical in a systems design the largest antenna gain per unit cost can be obtained at the highest technically developed frequency [Ref. 20]. Or more simply, the higher the operating frequency the more gain there is to be had per system dollar spent on antenna development. Table 1 illustrates this relationship for specific facilities.

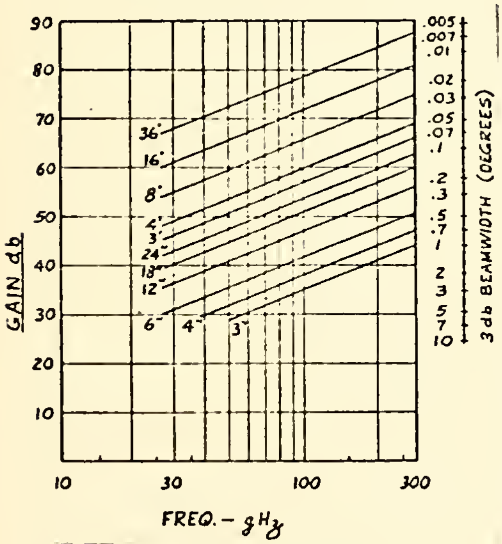


Fig. 3 Nominal gain and beamwidth of millimeter antennas.
From Reference 20

TABLE 1

Facility	f, GHz	D, ft	Gain, dB	Cost $/Rel. Gain
Arecibo Radio Obs. Puerto Rico	0.43	1000	60	6.0
NRAO, Greenbank W. Va.	1	300	56.6	1.8
Haystack Hill Lincoln Lab., Mass.	18	120	73.8	0.13
Prospect Hill AFCRL, Mass.	35	29	66.5	0.15
Aerospace, Calif.	250	15	78	0.0055
NRAO, Ariz.	180*	36	83.5	0.0035

* This system was not complete at time of writing. The figure is an estimate.

There are two interesting extremes in millimeter antenna technology. Small, high gain antennas do not appreciably increase the size of the systems in which they operate, while on the other hand, physically large antennas are capable of gains great enough for use in radio astronomy and ground based deep space communication probing and tracking. Between these two size extremes is the attraction of millimeter band antenna configurations for satellite application because of the relatively high gain for the size options available [Ref. 20].

An examination of the antenna configuration trade-offs will show which design is most suitable for the herein proposed spacecraft application. These trade-offs are the various antenna configuration characteristics and RF feed system alternatives. These configurations are the expandable truss, the array pattern sub-aperture design, or the single aperture, with each having either focal point, offset focus, or Cassegrain feed systems. Lens or lens horn feed systems also have certain 60 GHz potential applications [Ref. 20].

a. Expandable Antennas

Given a certain size limitation, the antenna dimensional accuracy depends upon the wavelength and reflector relationship. J. Ruze, in his work on antenna tolerance theory shows that the random surface error should be less than 0.015 inch (rms) with the systematic departure from the perfect contour being less than 0.08 wavelengths to prevent the occurance of significant gain loss [Ref. 21].

Because of these small tolerances, expandable antenna concepts are not feasible for spaceborn millimeter applications. Additionally, thermal distortion is a serious problem with expandable truss and other erectable type antenna structures [Ref. 18]. Consequently, the rigid structure, single or arrayed aperture antenna will be a basic design criteria with the maximum size limited by the launch vehicle shroud diameter, in the range of four to nine feet [Ref. 15].

With the expandable truss configuration, thermal distortion is a serious problem. This distortion is due to incident solar energy which may introduce excessive gain loss and beam deflection, a condition overcome only by sufficient structural rigidity and thermal shrouding.

b. Array Antennas - Advantages and Disadvantages

Thermal distortion is not a problem with the multiple aperture arrayed reflector antenna. With individual apertures of less than three feet, shrouding is unnecessary, low thermal gradients can be maintained, and light support structures will suffice.

Self-phased arrays inherently perform angle sensing and retrodirective functions even in the presence of satellite instability. Additionally, performance does not degrade when elements experience displacements or are mounted on non-planar surfaces. There are no moving parts and the array does not require absolute angle-of-signal-arrival measurement or absolute command pointing.

On the other hand, the aperture array antenna can be considered to involve more design complexity than the single aperture. In the self-phased array configuration each subreflector link is a separate processing channel (19 elements for a 60db antenna gain). Each channel element functions independently, and inherently adjusts the channel phase such that the particular link beam is redirected back toward the pilot signal source. Transmitter power must be diplexed (separated) among the channels requiring additional circuit complexity.

The arrayed antenna is more costly and adds considerably to the cross link equipment weight as compared to the single aperture antenna. For antenna gain requirements of less than 58db the array antenna is not cost effective, either in terms of design and fabrication or in terms of weight (cost) addition to the launch package [Ref. 18].

c. The Single Aperture Reflector

For a gain corresponding to an aperture diameter of less than or equal to 5 feet the single-aperture reflector antenna is most desirable. Where only several beamwidths of field-of-view are required for tracking, sub-reflector motion may be used in this configuration to provide an efficient, simple, low inertia, pilot beam signal steering technique.

The narrow beamwidth of such a high gain antenna will demand extreme beam pointing accuracy for initial lock-on

and tracking. A stabilization error of $\pm 0.1°$rms is achievable with a three axis inertial-wheel control system aboard the Advanced Technical Satellite-ATS-F, for example. Even this is a large angular uncertainty in the satellite attitude. Narrow beams from an EHF antenna of less than five feet (the antenna size to be specified) would require an attitude error measuring system which could be used to accurately steer the satellite antenna beam [Ref. 11].

It would appear, therefore, that automatic tracking is required to insure accurate pointing of the spacecraft antenna. Even so, the initial, or any periodic lock-on would require the assistance of lower frequency beacons and ground based computer complexes, regardless of antenna type [Ref. 16].

Utilizing ground control assistance, the methods available for maintaining the synchronous beamsteering accuracy are:

(1) attitude sensors utilizing IR horizon scanning

(2) RF phase and amplitude comparison

(3) optical star tracking techniques.

These methods can achieve accuracies in the range of 0.1 degree to a few arc-seconds (rms). These methods enable a satellite to accurately determine its attitude with respect to a known earth location and to simplify its beam pointing accuracy to another satellite.

The amplitude measuring technique can achieve a pointing accuracy of the order of a few tenths of a degree when tracking an RF ground reference signal. The phase measurement technique (interferometer) is more accurate and complex. An accuracy of ±10 arc-seconds has been reported at microwave frequencies [Ref. 22]. A suitable phase comparison technique, capable of measuring satellite attitude to a ±0.03 degree accuracy was developed for pointing a 0.3 degree antenna beamwidth aboard synchronous satellites.

Although development in this area is lagging behind laser optical developmental efforts, the EHF requirements have been presented for comparison. Such a proposed pointing and tracking system must include a ground controlled attitude sensing method, even though this would add significantly to the total system cost, possible over and above the comparable requirement for the laser system.

The ground control stations would monitor satellite position and orientation for initial synchronous beam pointing lock on. With ground station aid each satellite terminal receiver would be capable of coarsely establishing the direction of arrival of an acquisition aid or beacon signal from the opposite terminal transmitter. When beacon lock on occurs each terminal angle tracks on the signal and forms a high gain receive/transmit beam for information transfer.

It is expected that ground command accuracy of ±0.1° for initial beam pointing would facilitate the use of

a 0.2° beamwidth, 4.5 feet reflector diameter antenna for the proposed EHF satellite flight package [Ref. 22].

d. A Choice of Antenna Feed

For reflector diameters of less than 60 wavelengths, the region where Cassegrain feed systems block excessively, focal point parabolic reflector systems are used. On large size antennas, in the range of 300-400 wavelengths, the focal point feed, parabolic reflector feed system is also used because cost is the excessive factor for Cassegrain feed. Between 60 and 300 wavelengths of reflector diameter, the compatible range for 4-9 foot rigid structures, Cassegrain feed systems are most efficient and economical. Additionally, waveguide losses are very significant in focal point feed parabolic reflectors at 60 GHz.

e. A Lens Horn Antenna

Lens and lens horn antennas cannot compete with reflector types in the size range greater than 60 wavelengths in diameter. This is because of dielectric losses, weight, and fabrication costs. The lens horn configuration is best suited for short range handheld transceiver system applications [Ref. 13].

It is design cost and weight attractive at millimeter frequencies only for diameters up to 1 or 2 feet [Ref. 20].

f. Fabrication Material of the Single Aperture Configuration

With the antenna selective process now focused on the Cassegrain feed reflector in the 4-9 foot diameter

range, selection of the antenna fabrication material must be based upon the following considerations. The ideal antenna material should be strong, but light, have good thermal conductivity, a minimum thermal expansion coefficient, and be reasonably resistant to aperture distortion. Such distortion is caused by solar-induced thermal gradients. It introduces significant gain loss and beam squinting if enough structural rigidity and weight in the reflector are not used [Ref. 11].

A material known as "invar" has a slight expansion coefficient and beryllium meets the other desired criteria. Use of either of these materials is suitable for antenna fabrication of a 4-6 foot 60 GHz antenna with a weight on the order of 70-80 pounds including gimbals and drive motors [Ref. 16].

A relatively new material, consisting of graphite fibers embedded in an epoxy resin, has shown great promise as a lightweight structural material and can be tailored to display coefficients of thermal expansion lower than that of invar or beryllium [Ref. 24]. Philco Ford has done considerable fabrication experimentation with the graphite-epoxy composite [Ref. 24]. Their tests have indicated antenna distortion-induced gain losses of the order of 0.2db at 70 GHz for structures up to 6 feet in diameter.

A 19 inch diameter scale model antenna was made using this graphite-epoxy material in the reflective surface

on an aluminum subreflector and tested at 60 GHz. The feed was a single-aperture, multimode arrangement consisting of an electroformed horn, a machined-block mode launching section, and a hybrid ring for deriving sum and difference patterns. The horn was designed for a subreflector intercept angle of 13° and an edge taper of -10db. The achieved beamwidth was slightly wider than desired resulting in an edge taper on the subreflector of only 6.5 to 7db. Sidelobes present were attributed to the edge taper. The reflector was accurate at the test frequency to a very small error. It was concluded by this modeling that antennas constructed of graphite-epoxy are feasible for spacecraft applications offering the least weight addition and the most negligible antenna gain loss due to thermal distortion [Ref. 14].

Both General Electric and TRW Systems have investigated the use of aluminum, beryllium, and titanium as the basic material for the antenna and its back-up structure. Computerized thermal/structural analyses were used to establish the thermal distortion effects of solar energy impinging on parabolic antennas using various materials, supporting structures, finishes, and thermal control techniques. Results of these tests showed that beryllium or titanium could be used for reflector maximum diameters of 4-5 feet at 60 GHz with suitable dielectric shrouding to minimize thermal distortion. Within the accuracies of these analyses it was concluded that parabolic reflector antennas of greater than

five feet should not be designed unless significantly greater than proportional increases in size and weight can be tolerated [Ref. 18].

It is concluded from this analysis that a 4.5 foot reflector diameter Cassegrain-fed single aperture antenna fabricated from either titanium or graphite-epoxy resin is most suitable for each satellite of the space to space EHF link.

3. Power Source/Amplifier

In the laser system proposal, the choice of an operating frequency depends exclusively upon the choice of a laser source. For the conceptual comparative EHF system, selecting the 60 GHz operating frequency determines, within specific ranges, the millimeter wave signal source options.

Sources of low-level millimeter wave power in this frequency range include tubes and solid state devices. Sources of the tube type are classified as either klystrons, traveling-wave tubes, or magnetrons. The traveling-wave tubes are either backward-wave oscillators or traveling-wave amplifiers. The magnetrons are pulsed sources while the others are CW sources.

a. Tube Type Device Shortcomings

In each of these devices an electron beam interacts with the electric field components of stored or propagating electromagnetic energy. For such an interaction to be efficient the field components must be strong over the

entire cross-section of the electron beam. These field components fall off exponentially with distance away from the metal structure which supports them. Thus, at a distance greater than a portion of a free space wavelength from the structure, the fields become too weak to be of practical value. At millimeter wavelengths this leads to serious limitations in the space for electron beam passage, particularly in a conceptual spacecraft flight package [Ref. 17].

Additionally, backward-wave oscillators, klystrons, or traveling-wave tubes, used as the signal source, would require high operating voltages, ranging into the kilovolt region for even moderate amounts of power. This would require a relatively large and complex power supply and would create problems of heat generation, and reliability [Ref. 15].

Varian Associates of Canada, Limited, market a millimeter wave system transmitter candidate device called an Extended Interaction Oscillator (EIO), which is a linear beam tube. In this device, beam interception by the RF structure, which is a life shortening characteristic of reflex klystrons operating in the GHz region, is not a factor. Also, higher values of interaction efficiency may be obtained in the EIO. The device (VKE-2401) operates nominally at 60 GHz at an optimum load power output of 50 watts. With the voltage rating at 7 kVdc and current at 118 mAdc, this device exhibits a prime power requirement of 826 watts, or

6% efficiency at 50 watts output. Further, with a water cooling requirement and a no-distortion lifetime of only 3000 hours, the EIO is a dubious candidate for the spacecraft package [Ref. 25].

b. Solid-State Exciter Alternatives.

A solid state device for the transmitter-exciter power source is the logical choice for a spaceborne communication package. Such devices include IMPact Avalanche and Transit Time (IMPATT) diodes, IMPATT oscillators, and Gunn diodes [Ref. 26].

IMPATT diodes and complete oscillators are presently available for frequencies from 60-100 GHz at 100 mW, utilizing CW operation. Gunn effect devices are limited to a few tens of milliwatts output in the 50-70 GHz range. These are test results from Bell Telephone Lab [Ref. 15].

As reported to the Naval Electronics Laboratory (NELC) Microwave Conference in 1973 by representatives from Hughes Electron Dynamics Division, mechanically tunable V-band (50-75 GHz) IMPATT oscillators have been developed using packaged silicon $p^{+}n$ junction diodes [Ref. 27]. A 12-13 volt, 250 mA diode with a tuning bandwidth of 10 GHz has been successfully tested with a power of 175 mW at 60 GHz. Such device availability offers greater system design flexibility, e.g., multichannel time division multiplexing. Laboratory testing of this device included air cooling to maintain a temperature of 230°C.

A diode device known as Limited Space Charge Accumulation diode (LSA), an extension of the Gunn diode technique, offers greater output power capabilities [Ref. 15]. LSA devices are theoretically capable of greater efficiency as well as power output (12% and 3.5 watts at 60 GHz) than silicon IMPATTS because they currently display higher performance under pulsed conditions. Current material and thermal technology has favored the silicon IMPATT diodes, although heat sink developments for gallium arsenide devices are improving the technical capabilities of LSA diodes [Ref. 16]. The LSA device appears to be the "quietest" source at millimeter frequencies [Ref. 18]. This suggests the LSA device to be a likely receiver local oscillator candidate.

c. A Solid-State Excited Traveling Wave Tube Amplifier

T. Misawa of BTL reported that CW power levels of over 500 mW have been obtained from silicon avalanche diodes at 55 GHz and 100 mW at 107 GHz under laboratory conditions [Ref. 16]. Coupled with upconverter technology (to be discussed later) such IMPATT diodes can serve as the exciter source for a traveling-wave tube amplifier. For example, a transmitter-exciter output power of 60 mW is required to drive a 30db gain 40 watt traveling-wave tube amplifier. More power is required to drive a lower gain (20 watts) and lighter weight traveling-wave tube amplifier

(TWTA). G. Kefalas reports that cavity coupled TWTA's can eventually be developed to provide 20-50 watts RF output with an overall efficiency of 30 percent could be achieved at reasonable weights with the 20-25 watt range the current state-of-the-art [Ref. 18].

Current communication satellites utilize the long life traveling-wave tube amplifier with a helix slow wave structure. The design problem in adopting TWTA's to millimeter wave frequencies has been the very small helix diameter and the difficulty of forming and controlling the fine beam required to traverse the slow wave structure. Coupling this structure with a permanent magnet facilitates an RF power level of up to 150 watts at frequencies up to 94 GHz in a conduction cooled tube. The magnet weight renders such tubes much heavier than those used in the microwave spectrum.

Utilizing the IMPATT diode as transmitter exciter requires a multiple section amplifier tube to achieve adequate gain [Ref. 16]. Within the state-of-the-art, 10-15db gain can be achieved in a TWTA of 20 watts RF, coupled with the solid state IMPATT diode power source at 175 mW, described previously as tested by BTL, to form the transmitter.

d. Frequency Stability Control

An additional factor to consider is that the transmitter frequency drift must be minimized in order to

avoid the necessity of employing excess receiver bandwidth to compensate for frequency drift. The extra bandwidth would reduce receiver sensitivity which in turn would require the use of additional transmitter power. As a minimum, frequency stability should be from ±0.10 to ±0.01 PPM per degree centigrade. To achieve frequency stability in millimeter wave oscillators, such as the TRW avalanche device, a stable reference frequency must be used. Frequency or phase locking the millimeter wave source to a highly stable crystal controlled oscillator, perhaps the best technique, can be used with both tubes and solid state sources. A technique employed by TRW Systems in their avalanche amplifier and the most effective method for solid state devices is called injection locking. A sample of the stable reference frequency is injected into the main oscillator, which then becomes frequency locked to the reference frequency. The reference frequency power level is dependent upon the frequency separation between it and the frequency to be locked and is generally 15 or 20db below the signal [Ref. 15].

Conclusions reached by G. Kefalas indicate that solid state devices such as the IMPATT diode can be developed as the 60 GHz system transmitter exciter [Ref. 18]. This will provide reliability, efficiency, injection locked operation for frequency stability, and low noise performance.

e. Alternative Transmitter Configurations

An alternative transmitter configuration is an all solid state varactor frequency multiplier chain or diode

oscillator array [Ref. 28]. Additionally, output power levels greater than 250 mW have been achieved with silicon IMPATT diode amplifiers in Ka and V band frequencies [Ref. 26]. The output power level of millimeter wave IMPATT diode amplifiers can be extended to the one watt level by using IMPATT diodes with double drift regions [Ref. 29]. A number of these diodes could possibly be arrayed for use as the final stage in an all solid state transmitter [Ref. 12].

Furthermore, an avalanche oscillator amplifier has been developed by TRW Systems for the 55-65 GHz range [Ref. 30]. It provides an output power of 100-200 mW at 5-7% efficiency with a gain of 23db and a bandwidth capability of 1.3 GHz. Although the all solid state transmitter configuration could have real future applications, such as with a complex channelized arrayed antenna, it will not be further considered for this proposed system, since, coupled to the single aperture 4.5 foot antenna, a 250 mW to one watt transmitter level will not provide a signal to noise ratio comparable to that of the laser/optical proposal.

f. FM Heterodyning

FM heterodyning is considered the most feasible modulation scheme for a number of reasons. It offers circuit simplicity at the specified BW of 30 MHz. Additionally, the need for an external modulator is negated, and associated power loss avoided, since the IMPATT exciter (of the

transmitter configuration) is easily FM'd by modulating its' bias current. Typical frequency versus bias current sensitivity is 2 to 10 MHz per mA. The FM characteristic along with the IMPATT bias current control circuit serves as a "signal lock-on" feature, eliminating the need to frequency stabilize the transmitter [Ref. 23].

g. The Selected Power Source/Amplifier

The proposed transmitter will be a 20 watt TWTA excited by a 60 GHz, 175 mW IMPATT diode, frequency modulated, power source. The following discussion of solid state upconverters is pertinent to this analysis, even though a frequency multiplier chain will not be shown in the chosen system configuration, because it represents a viable transmitter design alternative utilizing stable S-band solid state components; however, it could be expected to involve relatively more complex circuitry and higher cost [Ref. 18].

4. <u>Solid State Frequency Upconverters</u>

For the system configuration in which a frequency translation transponder is required to boost the solid state source frequency, an upconverter is used. This component must be pumped 8-10db above the signal output drive level to the TWTA. In this configuration an IMPATT at 250 mW would only be able to supply sufficient pump power for an upconverter output maximum of 25 mW. Supplying an IMPATT as an amplifier following the upconverter would increase the

drive to the TWTA. This feasibility was demonstrated by Sie and Crowe [Ref. 16].

The broadband varactor doubler/upconverter was designed and tested by TRW Systems to efficiently upconvert a 2 GHz wide S-band signal to a Ka-band [Ref. 30]. Such a device is reported to be capable of V-band conversion [Ref. 18].

Such frequency multiplication can be achieved utilizing low power components in varactor diode chains (upconverters) for the indirect generation of power. System output power is normally limited by the final multiplier diode and the overall bandwidth tends to be narrow while the DC to RF conversion is low [Ref. 12]. The varactor multiplier chain is a carefully designed complex assembly and is relatively expensive. The fundamental frequency is usually obtained from a highly stable, temperature-controlled crystal oscillator. Stabilities as high as several parts in 10^7 can be achieved [Ref. 15].

Considerable frequency multiplier testing has been conducted at MIT and Sylvania to achieve output frequencies up to 75 GHz [Ref. 18]. This testing has shown, however, that allowing for filtering and coupling component losses, the multiplier chain is far less efficient than direct solid state transmitter excitation at 60 GHz.

5. Low Noise Receiver

There has been a lack of low noise millimeter wave receiver amplifiers for the 60 GHz region [Ref. 28]. Ground

terminals have traditionally used parametric amplifiers to obtain a low noise temperature. These have not been sufficiently reliable for use in space communications, partly due to the klystron pump sources. Solid state pump sources have been used more effectively at S-band and higher frequencies [Ref. 16].

a. Parametric Amplifier Shortcomings

A minaturized nondegenerate Ka-band parametric amplifier applicable to earth-to-satellite systems has been developed by AIL, a division of Cutler-Hammer, Inc., [Ref. 31]. This amplifier is designed to operate in the range of 36-38 GHz with an instantaneous bandwidth of 100 MHz. A gain of 18db with a noise figure of 3.8db was achieved, using a solid-state pump at 101.4 GHz. This parametric amplifier and pump assembly are thermally stabilized and designed to withstand rugged environments. Such an amplifier has been postulated by a U.S. Air Force study for an eventual inter-satellite 60 GHz link receiver system, although they are not current state-of-the-art [Ref. 18].

The performance of conventional tunnel diodes and parametric amplifiers, such as just described, used in the C and X band of the spectrum for current satellite communication applications decreases rapidly at V-band frequencies such as 60 GHz [Ref. 15]. Therefore, with a lack of low noise millimeter wave amplifiers for a 60 GHz receiver, the receiver sensitivity will be dependent upon the mixer characteristics [Ref. 28].

b. The Shottky Barrier Diode Mixer/Detector

At the 60 GHz millimeter wave band the Shottky barrier diode mixer is the likely receiver candidate component. Bell Labs have demonstrated 5-6db conversion losses at 58 GHz with the Shottky barrier balanced diode mixer together with a low noise transistor amplifier such as the Texas Instruments L-209; whereas, more conventional mixers (tunnel diode and paramps) have exhibited noise figures ranging from 10-15db [Ref. 32].

An average conversion loss of 8db has been obtained at 94 GHz by ADTEC Laboratories and 7db by Aerospace Corporation using a Shottky barrier three diode mixer configured receiver. For the proposed system, based on these findings, a receiver noise figure of 7db will be assumed. Likewise, the inter-satellite link will require three such balanced mixers in the receiver configuration [Ref. 16]. Additionally, greater reliability can be achieved with this diode mixer configuration due to unique fabrication techniques [Ref. 15].

For the receiver detector, point contact PIN diodes are laboratory proven for this specified application. At the chosen frequency of 60 GHz, diodes fabricated in the manner of the Shottky barrier mixer diode, but with a change in barrier metallization, have surpassed the performance of point contact diode in terms of reliability and uniformity [Ref. 26].

Developments at Martin Marietta Corporation resulted in the conclusion that point contact diode mixers will exhibit a noise figure of 10db with a 1 GHz IF and an IF noise figure of 2.5db. The 1 GHz IF permits both a wide instantaneous bandwidth and low noise performance without balanced mixer operation [Ref. 18].

c. A Balanced Mixer Receiver

Although balanced mixer operation is not necessary for low noise performance when operating at a high IF, it permits the most efficient use of local oscillator power and simpler local oscillator coupling techniques than for a single-ended mixer operation. Balanced mixer operation with high IF provides redundancy for improved reliability in the event of single diode failure. This redundancy, IF configuration, and local oscillator will add 5db to the already specified 7db noise figure of the Shottky barrier balanced mixer receiver to be specified for this system [Ref. 18].

d. Receiver as Radiometer

The presence of a millimeter wave receiver in the satellite flight package offers additional side benefits. Such a receiver could easily be made dual-purpose. It could operate as both a radiometer, for measuring the temperature of deep-space, the sun, and the earth's atmosphere, and as a receiver. At 60 GHz, for example, these observations would be impossible from the earth's surface because of atmospheric absorption [Ref. 11].

6. Local Oscillator

In the case of a superheterodyne receiver, which is a basic premise in this proposal, the local oscillator power requirements are a severe constraint. The size, weight, high cost, limited lifetime, and low efficiency of reflex klystrons or backward wave oscillators and their high voltage power supplies used as the local oscillator would negate many of the other desirable features of 60 GHz millimeter wave candidate receivers. Solid state sources have largely eliminated these shortcomings of vacuum tube local oscillator sources [Ref. 33].

While the IMPATT diode will be the most efficient exciter/driver for the 20 watt traveling-wave tube amplifier configuration, the driver noise performance becomes more critical when a solid state local oscillator device is specified. IMPATT diodes are more noisy in comparison to Gunn effect devices with respect to both AM and FM noise. With care in circuit design, to insure low FM noise, Gunn diodes are feasible as the receiver local oscillator [Ref. 15].

It should be noted, however, that the noise performance becomes a function of the quality of the reference frequency when using the Gunn effect device as local oscillator. It will also require at least 20 mW to furnish power for the three balanced mixers in the specified receiver configuration [Ref. 16]. In the design and testing of the miniaturized parametric amplifier by AIL of Cutler-Hammer.

as discussed previously, a Gunn diode oscillator power level of 20 mW was achieved [Ref. 31]. A balanced IF configuration is within the state-of-the-art and can be tuned with the Gunn diode local oscillator, Shottky barrier mixer/receiver configuration [Ref. 26].

The LSA diode device has all the advantages of the Gunn diode for local oscillator application and additionally is more efficient. As mentioned previously, it is also the "quietest" solid state device [Ref. 18]. It will therefore be selected as the local oscillator source for the system proposal.

7. Passive Components

A number of key passive components are required in developing complete transmitter and receiver subsystems, including filters, circulators, and waveguide feeds. The unique common features among these components are that they are all electroformed and fix-tuned. TRW Systems, has developed and laboratory tested all such components in the 55-65 GHz range. Device bandwidths ranged from 20 MHz to 5 GHz with insertion db losses in the range of 0.2 to 0.3 with isolation ranging from 25-30db. All components were evaluated over the range 60 to 100°C with only minimal performance changes [Ref. 30].

In previous millimeter wave design applications conventional microwave fabrication techniques have been applied to passive components. The results have been

unpredictable performance and high losses as they were not uniquely electroformed as is now the case with EHF component development with these techniques. TRW Systems and Bell Labs have demonstrated successful fabrication and greatly improved performance of components such as antenna feeds, hybrids, filters, and assemblies [Ref. 16].

An evaluation of circular helix waveguides and components has shown that this type of transmission medium exhibits the unique property of decreasing attenuation constant with increasing frequency (TE_{01} mode) [Ref. 18]. Very little signal distortion over long lengths has been achieved at 60 GHz. Thus, this transmission medium offers a particularly attractive means of minimizing feedline loss in the proposed system.

D. SELECTED COMPONENT CONFIGURATION/DESCRIPTION

As a synthesis of the foregoing hardware component review the 60 GHz, 30 MHz bandwidth satellite link package will consist of the following:

1. A 4.5 feet diameter, single aperture, Cassegrain fed, parabolic reflector, transmit/receive antenna will auto-track (with ground based beacon assist) the arriving signal from the associated terminal. The Cassegrain configuration will perform beam motion (2 or 3 beamwidths off boresight) by subreflector movement. Acquisition or lock on will occur when the received pilot signal is maximized in amplitude and

meets a threshold level to form a high gain receive/transmit beam for information transfer.

2. The Shottky barrier balanced diode mixer will be configured as close to the antenna as possible. Helix waveguide transmission media will be utilized to minimize RF feed losses. The balanced mixer is the "front end" of the superheterodyne FM receiver, which includes a low noise transistor amplifier such as the Texas Instruments L-209. Coupled to the receiver is the 60 GHz IF circuitry for maximum use of local oscillator power, efficient coupling techniques, and redundancy for increased reliability. The detector circuitry is of the point contact PIN diode type fabricated in the manner of the Shottky barrier mixer diode.

3. The local oscillator will be a 20 mW LSA diode oscillator driver device operated in a waveguide terminated in a short to form a cavity. The external Q of such a cavity will be between 200 and 500 [Ref. 18]. The noise content of the LSA diode depends upon the design of the baseband circuit because this circuit has negative resistance. Therefore, the baseband circuit design for the local oscillator is a critical consideration.

4. The transmitter consists of a 30% efficient 20 watt cavity coupled traveling-wave tube amplifier, excited by a 175 mW "injection-locked" 60 GHz IMPATT diode modulator/driver oscillator. Frequency modulation is achieved by

the "signal lock-on" feature of the FM characteristic with the IMPATT bias current control circuit.

As with the laser system description the signal processing/telemetry technology has been described elsewhere and will not be addressed in this component selection.

IV. COMPARISON OF EHF AND LASER SYSTEMS

A. SYSTEMS' PERFORMANCE AS MEASURED BY SIGNAL-TO-NOISE RATIO - SNR

It is often difficult to arrive at an acceptable basis for comparing systems which employ different basic principles. This is not basically a problem of being unable to assess performance relative to the incurred penalty or burden, but more a problem of interpreting subtle details that restrict the freedom of choice within the system and assess practical difficulties and limits in various technology areas. The ultimate criterion for a comparison of two competitive communication systems is the signal power delivered to the receiver relative to the noise power at the receiver. This is commonly expressed in a ratio called the signal-to-noise ratio (SNR). Within the performance calculations for the millimeter wave and optical satellite to satellite link, some instructive comparisons can be made. By specifying the bandwidth and the detection method for the two systems, a multitude of variables have been eliminated and emphasis has been concentrated on the more salient features of the signal-to-noise ratio calculation. The SNR for a radio or optical heterodyne system is:

$$\frac{S}{N} = \frac{P_T G_T G_R L}{N_1 B}\left(\frac{\lambda}{4\pi R}\right)^2$$

where:

S = Signal power (W)

N = Noise power (W)

N_1 = Noise power density (W/Hz)

P_T = The power transmitted (W)

R_T = Gain of transmitting antenna

G_R = Gain of receiving antenna

B = Noise bandwidth

λ = Wavelength

L = Miscellaneous losses in the system due to hardware, atmosphere, mispointing, etc.

R = Range

1. Power Budget for Each System

Tables 2 and 3 summarize the performance characteristics calculated for the EHF and Laser systems respectively.

2. Transmitter Output Power - P_T

Although 2 watts of output power was specified for the laser system, additional power output is available. Single-frequency, frequency-stabilized, and tunable lasers are commercially available with up to 10 watts of output power from such manufacturers as GTE Sylvania and RCA Ltd., Research and Development. With this power output, the SNR would be increased by 7db over the proposed system if everything else remained constant. However, this increase in power might present a major difficulty in spacecraft design due to the increased heat dissipation requirement. With a

TABLE 2

CHARACTERISTICS OF THE CO_2 LASER SPACE-COMMUNICATION LINK

OPERATING WAVELENGTH (λ) = 10.6μm	
OPERATING FREQUENCY (f) = 2.83×10^{13}Hz	
TRANSMITTER OUTPUT POWER (Pt) = 2 watts	3.0 dBW
TRANSMITTER ANTENNA GAIN (Gt) = $\frac{4\pi^2 r^2}{\lambda^2}$ r = 2.5 inches	91.5 dBW
RECEIVER ANTENNA GAIN (Gr) = (Gt)	91.5 dBW
PATH LOSS $(\lambda/4\pi R)^2$ R = 73,000km	-278.8 dBW
TRANSMITTER OPTICAL LOSS	- 3.0 dBW
RECEIVER POWER (Pr)	- 95.8 dBW
STANDARD NOISE POWER DENSITY $(\frac{hf}{\eta\lambda})$	-190.3dB(W/Hz)
NOISE FIGURE OF RECEIVING SYSTEM	12.6 dBW
NOISE BANDWIDTH (B) = 30 MHz	74.8 dBW
SNR	7.1 dBW

TABLE 3

CHARACTERISTICS OF THE 60 GHz SPACE-COMMUNICATION LINK

OPERATING WAVELENGTH (λ) = 5mm	
OPERATING FREQUENCY (f) = 60 GHz	
TRANSMITTER OUTPUT POWER (Pt) = 20 watts	13.0 dBW
TRANSMITTER ANTENNA GAIN (Gt) = $\frac{4\pi^2 r^2}{\lambda^2}$ $r = 2.25$ ft.	53.5 dBW
RECEIVER ANTENNA GAIN (Gr) = (Gt)	53.5 dBW
PATH LOSS $(\lambda/4\pi R)^2$ R = 73,000km	-226.0 dBW
TOTAL GUIDE LOSSES (L)	- 3.0 dBW
RECEIVED POWER (Pr)	-109.0 dBW
STANDARD NOISE POWER DENSITY (kT ambient)	-204.0 dB(W/Hz)
NOISE FIGURE OF RECEIVING SYSTEM	12.0 dBW
NOISE BANDWIDTH (B) = 30 MHz	74.8 dBW
SNR	8.2 dBW

transmitter efficiency of 10%, the amount of heat to be dissipated would increase from 18 watts to 90 watts as the power is increased to 10 watts. At a dissipation rate of 0.53 W/ft^2 from a passive radiator, a 10 watt laser would require 47.7 ft^2 of radiation surface to maintain the laser at 100°K [Ref. 7].

The major limitation in the design of a competitive spaceborn laser communication system is the lifetime of the laser itself. The operating lifetime should be in the range of 3 to 5 years. To date the longest lifetime reported for a sealed-off laser discharge tube is 12,000 hours [Ref. 5]. This represents approximately one-half the minimum required operating lifetime. The higher power commercially available lasers mentioned above have a warranty for one year of continuous operation. It is reasonable to assume that operating lifetimes will continue to increase in the future since no fundamental breakthrough is believed necessary in this area. Possible alternatives to a single sealed-off laser discharge tube include the possibility of using multiple sealed-off tubes or refillable tubes. Both alternatives are feasible but would considerably increase the weight and complexity of the satellite. The increased operating lifetime of a sealed-off discharge tube offers the most promise for the future.

For the proposed EHF system a 20 watt TWTA was specified as current state-of-the-art although a Martin Marietta

study for the U.S. Air Force [Ref. 18] projects the near future availability of space capable TWTA's up to 50 watts RF. Postulating such a transmitter in the given system would add 4db to the present SNR. Such a design change would certainly entail extensive heat dissipation engineering, something which has yet to be addressed by any comercially prepared millimeter wave space communication link proposal.

The basic problem when confronting the question of, "What will be the EHF system component lifetime?", is that beyond the laboratory no definitive answer exists. The basic technology necessary to implement suitable components for the postulated crosslink for a 3 to 5 year lifetime exists today, but development of space-qualified TWTA's having the required performance is only a projection.

3. Antenna Power Gain - G_T/G_R

Since for the laser system the same aperture serves as both the transmitting and receiving antenna, the power gains are equal and can be considered together. The antenna system described consists of a 5 inch diameter aperture telescope and a coarse beam-pointing mirror reflector with a power gain of approximately 91.5db. Antenna power gain is directly proportional to antenna aperture; therefore, the gain can be varied to any given amount by varying the diameter of the aperture within limits. By increasing the diameter to 10 inches, the gain is increased to approximately

96.5db, an increase of 5db over the 5 inch diameter aperture. It is important to remember that this is the increased gain for one antenna; therefore, the total gain of the link can be increased by 10db by doubling the aperture from 5 to 10 inches in diameter. This increased gain is not free, however, because an increase in weight and cost will accompany such a change. By using the methodology used in Ref. 34, the increased gain would cost approximately $495,000 and increase weight by 10 pounds for each of the two satellites. A second important consideration associated with antenna power gain is that beamwidth is inversely proportional to aperture. The diffraction limited beamwidth of the 5 inch aperture is 102 microradians while that of the 10 inch aperture is 51 microradians. Two geostationary satellites are not stationary. They move at the same scaler speed, but their vector velocities differ by a tangential component of magnitude V_T = 5.3 km/sec. The point ahead angle is approximately $\theta p = 2(V_T/c)$ = 11 microradians. If the antenna beamwidths are of this size or smaller, the two satellites cannot communicate by transmitting and receiving along the line-of-sight between satellites. This consideration sets the upper limit on antenna aperture and the gain if the complexities of point-ahead angle are to be avoided. For a beamwidth of 22 microradians (100% safety margin) the antenna gain would be approximately 105.7db.

As with the laser system, the EHF antenna aperture serves for both transmitting and receiving; therefore, the power gains are considered together at 53.5db. Since antenna power gain is directly proportional to antenna aperture, consideration should be given to the feasibility of increasing the antenna aperture to achieve more gain, thus an improvement in the SNR.

The most efficient, lightweight, and practical antenna aperture for the proposed EHF system was found to be the Cassegrain-fed parabola. However, a large single-aperture parabolic reflector for gains = 58db or greater is subject to severe thermally induced aperture distortion in the space environment, resulting in excessive loss of aperture gain. The addition of structural rigidity to reduce aperture distortion to an acceptable level would be expected to result in excessive crosslink equipment weight. The maximum practical all-metal single-aperture diameter for acceptable pointing accuracy (in the presence of the space thermal environment) would be about 5.3 feet, corresponding to approximately 58.5db antenna gain. Based on the EHF system described in this paper, to achieve a system SNR of 20db, the system design would have to incorporate the multiple-aperture or array antenna of nineteen highly directive elements [Ref. 18]. Such a self-phased array could provide accurate angle-sensing and beampointing with a total cross link antenna gain of 120db. It would add approximately 111

pounds to the proposed EHF communication package weight, since a nineteen element self-phased array antenna and unique subassemblies can be estimated to weight 181 pounds [Ref. 18], whereas, the 4.5 foot single-aperture proposal can be estimated to weight 70 pounds [Ref. 16].

Such a package weight increase, exclusive of other system component change requirements (and associated costs), would add over $1 million to the launch cost of each terminal, considering the probable launch cost of $10,000 per pound [Ref. 2]. While the more sophisticated array system would offer a 100 MHz [Ref. 18] bandwidth at the 20db SNR, such an improved potential would have to be measured against the greater cost.

As mentioned for the laser proposal there can be inherent point-ahead angle complexities with the antenna configuration. While the 5 inch telescope of the laser proposal has a diffraction limited beamwidth well within the 100% safety margin of 22 microradians, to account for the point-ahead angle of 11 microradians, the conceptual EHF 4.5 foot antenna would exhibit a comparable diffraction limit of 9.5 microradians, which does not cover the point-ahead angle. This complexity can be avoided with the proposed EHF antenna by it's specified beamwidth of 0.3° as long as either angle-sensing, aperture gimballing, or Cassegrain subreflector scanning of 3-4 beamwidths is incorporated [Ref. 18]. This would also necessitate greater design

complexity and added circuitry and weight for the EHF antenna design; therefore, from the standpoint of antenna pointing accuracy and tracking, the laser proposal would appear more favorable.

4. Noise Power - N_1B

At optical frequencies, the dominant contribution to the noise spectral density (N_1) is given by hv where h is Plank's constant and v is the operating frequency. The quantum noise (hv) results from the particle nature of radiation and increases linearly with frequency. The noise power at a spacecraft receiver for a given bandwidth (B) is thus hvB where h = 6.624×10^{-34} watt-sec^2 and v = 2.83×10^{13} Hz (CO_2 - 10.6 microns). For the laser system specified in this paper NB is equal to 5.63×10^{-13} watts or -122.49 dbW. In contrast to the optical frequencies the dominant contribution to the noise spectral density at radio frequencies is given by kT where k is Boltzmann's constant and T is absolute temperature. The thermal noise (kT) results from thermal fluctuation of electrons in a resistor. The noise power at a spacecraft receiver for a given bandwidth is thus kTB where k = 1.38×10^{-13} joules/K° and T = 300°K. For the 60 GHz system specified in this paper NB is equal to 1.24×10^{-13} watts or -129.06 dbW. It can thus be seen that the 60 GHz EHF system has the advantage of approximately 6.5db less noise power to overcome than does the CO_2 laser system.

5. Space Loss

The space loss of a communication system is given by the formula $(\lambda/4\pi R)^2$ and is therefore specified by choosing the operating wavelength (λ) and the communication range (R). The only way to reduce space loss, given the operating wavelength, is to position the satellites closer together. This is feasible when considering only two satellites, but not when considering a tri-satellite system for around the earth communication.

6. Miscellaneous Losses - L

These losses are composed primarily of two sources for the laser system. First is the loss due to the optical components of the system. These include losses from beam-splitters, directive mirrors, telescope, and the image-motion compensator. These losses combine to give an estimated signal loss of 3db. The second source of loss is also the loss due to optical components associated with the receiver section plus the loss generated by the receiver itself as given by the noise figure of the receiver. The total loss for the receiver is approximately 12.6db.

As discussed for the EHF system, the balanced diode mixer receiver has a loss of 7db while the IF circuitry adds 2.5db for a total receiver noise figure of 12.5db. The estimated miscellaneous signal loss of 3db is due to waveguide and any necessary passive components such as filters, hybrids, or circulators as determined by the system engineering.

B. COMMUNICATION SYSTEM OPTIMIZATION METHODOLOGY

Many complex relationships exist between the performance parameters of a communication system and its fabrication cost, weight, volume, and power requirements. A communication system optimization methodology, applicable to both optical and radio systems, has been proposed in Refs. 34 and 35 to provide the systems designer with the optimum values of the major system parameters of a communication system. This methodology optimizes the communication parameters such that either the lightest or least expensive system is derived, within the performance constraint imposed. It is therefore necessary to represent the various component parts of a communication system in terms of weight, cost, and power. The following components have been so represented: transmitting/receiving antenna, transmitter/receiver acquisition and tracking system, transmitter modulator, receiver demodulator, transmitter/receiver power conditioning, transmitter, and spacecraft heat rejection system. Basically, the optimization procedure develops system cost relationships as a function of the values of these system parameters. The cost relationships include the fabrication costs of the system components, the cost of placing the components aboard a spacecraft, and any other pertinent systems costs. With the cost relationships of the components developed, the total system cost can be minimized as a function of the values of the major system parameters under the constraint that the specified performance criterion

is achieved. Confidence in the burden relationships developed be this methodology varies strongly on the component in question. As a general rule, cost burdens are considerably more nebulous than weight burdens [Ref. 34]. For such components as photovoltaic power supplies, space radiators, launch costs, and perhaps antennas and optical apertures, the relationships can be expressed with reasonable certitude. On the other hand, burden relationships for space qualified transmitter sources (both optical and EHF) and precise pointing systems required are known with less confidence. These burden relationships will continue to evolve in the wake of technological advance and fuller understanding of the many diverse technologies represented. The communication system optimization methodology presented in Appendix A has been applied to the baseline 2 watt laser system described in this paper for the purpose of illustration. Table 4 contains the output from this methodology. By specifying the system bandwidth, satellite position, and detection method, the signal-to-noise ratio at the receiver is primarily a function of transmitter output power and antenna gain. To carry this methodology a step further, an iterative process of varying these two parameters relative to a given SNR was undertaken in order to select an optimum system. This iterative process was accomplished for the various 7dB and 20dB SNR systems and the results are presented in Figure 4. It can be seen that for a performance criterion of 7dB SNR, the optimum system

TABLE 4

COMPONENT	WEIGHT (lb)	POWER (W)	FAB. COST ($)	LAUNCHED* COST ($)
xmtr/rcvr antenna	33.12	-	51,714	382,914
acq. and track. sys.	44.31	27.21	1,507,600	1,950,900
xmtr	29.00	20.00	10,000	300,000
modulation system	11.00	55.00	30,000	140,000
demod. sys.	56.00	176.50	30,500	590,500
heat reject. sys.	.45	-	13,836	18,336
prime pwr. sys.	18.20	-	19,239	182,000
total	192.08	272.77	1,662,892	3,564,453

*launch vehicle cost - $10,000/lb

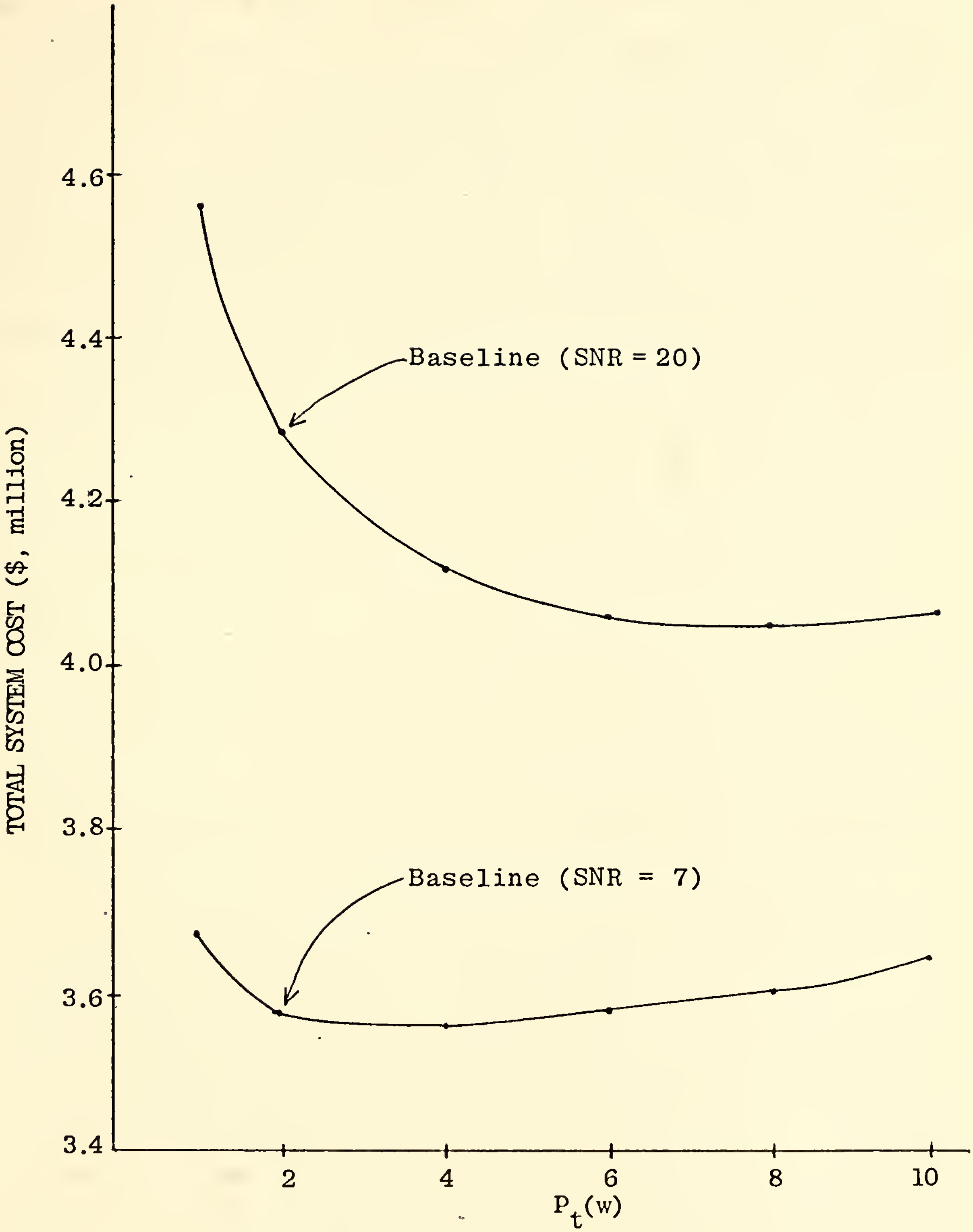

TOTAL SYSTEM COST ($, million)
4.6
4.4
4.2
4.0
3.8
3.6
3.4
Baseline (SNR = 20)
Baseline (SNR = 7)
2
4
6
8
10
P_t(w)

Figure 4

has a transmitter power of 4 watts, antenna aperture of 4.2 inches (10.73cm) and a system cost of approximately \$3.57 million. For a 20dB SNR, the optimum system has a transmitter power of 8 watts, antenna aperture of 7.37 inches (18.72cm) and a system cost of approximately \$4.05 million. In order to compare systems with different signal-to-noise ratios, it is appropriate to relate them on the basis of cost per unit channel capacity. The general expression of channel capacity was developed by Shannon and is given as follows: [Ref. 36]

$$C = B \log_2(1 + S/N)$$

where

C = channel capacity

B = bandwidth

$$\text{Cost per unit channel capacity} = \frac{3.57}{\log_2(1 + 7)} = \frac{4.05}{\log_2(1 + 20)}$$

for the 7dB and 20dB systems respectively where B and a factor of 10^6 dollars are common to both systems. On this basis, the 7dB system has a cost/unit channel capacity factor of 1.19 while the 20dB system has a factor of 0.92. Thus, it is apparent that the 20dB system optimizes this cost/unit channel capacity relationship. This optimization methodology

can also be applied to the 60GHz system proposed in this paper and similar results obtained. However, the quantitative relationships of the system parameters and costs, weights, and powers for the 60GHz system have not been established, thus a direct comparison on a cost basis is not possible. However, the values calculated for the laser system serve as a point of reference or upper limit for the cost of a 60GHz system of equal capacity.

The values presented in Figure 4 and Table 4 have been calculated for a single satellite. These values can be multiplied by 2 and 3 for bisatellite and trisatellite systems.

V. CONCLUSIONS

It has been shown that a need exists for a high data rate satellite to satellite trunking system for both commercial and military applications. It is concluded that both the CO_2 laser and 60 GHz systems are viable alternatives to fulfill this need. Both systems include components that are in the developmental stage. Space qualified components are lacking for both systems, specifically the traveling wave tube amplifier as the EHF transmitter, and the laser transmitter sources. Present lifetimes are approximately ½ the projected requirement of 3-5 years. It is believed that with the inclusion of solid-state IMPATT diode sources at 60 GHz and sealed-off oscillator tubes for the CO_2 laser, that the lifetimes requirement will be met in the relatively near future.

For the link of interest in this paper, the EHF system is inherently superior to the laser system in two areas due to the wavelengths involved. These are a space loss advantage of approximately 53dB and an advantage of approximately 14dB due to the different noise characteristics of the two systems. In contrast, the laser system has the advantage of appoximately 38dB antenna power gain for each antenna. Associated with this greater antenna power gain is the added advantage of less weight and associated cost for this laser system. For the baseline systems described, the EHF system

would require additional complexity in the acquisition and tracking system. This increased burden is not necessary with the 102 microradian beamwidth of the laser system. Other performance parameters for the two systems are basically equivalent. A direct comparison of the two systems utilizing the communication system optimization methodology was not possible because the detailed relationships of cost, weight, and power to system performance have not been commercially developed for the EHF components. However, this methodology allows for the investigation of CO_2 laser systems, for which commercial costs have been developed, and a baseline standard selected in terms of cost and weight for given comparable performance parameters. Using such a standard, future EHF and laser proposals can be evaluated for the selection of an optimum link for synchronous satellite trunking.

APPENDIX A*

COMMUNICATION SYSTEMS OPTIMIZATION METHODOLOGY

A.1 INTRODUCTION

The complexity of evaluating the relative roles of systems for future spacecraft communication and tracking applications, considering the broad spectrum of potential manned and unmanned space missions, demands a unified methodical approach. As shown in Figure A-1, the task is one of examining the study data compiled by communication components analysis, and communication systems analysis studies; and then determining the optimum parameters for communication systems. In brief, the communication components analysis task provides data on the system parameters with relationship to the fabrication cost, weight, size, etc., of the component implementation. The communication systems analysis provides the relationships between the communication parameters, noise effects, and system constraints. While the general goals of the systems optimization task can be stated rather simply, its implementation will require a significant amount of effort due to the large number of parameters that must be considered.

This communication systems optimization methodology section is divided into sub-sections which treat the general optimization procedure for communication systems, followed

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* This Appendix is taken verbatim from Ref. 34 with the quantities utilized in Table A-1 extracted from Refs. 34 and 35.

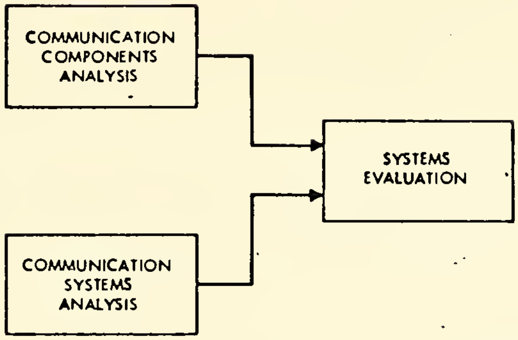

Figure A-1. Systems optimization flow chart.

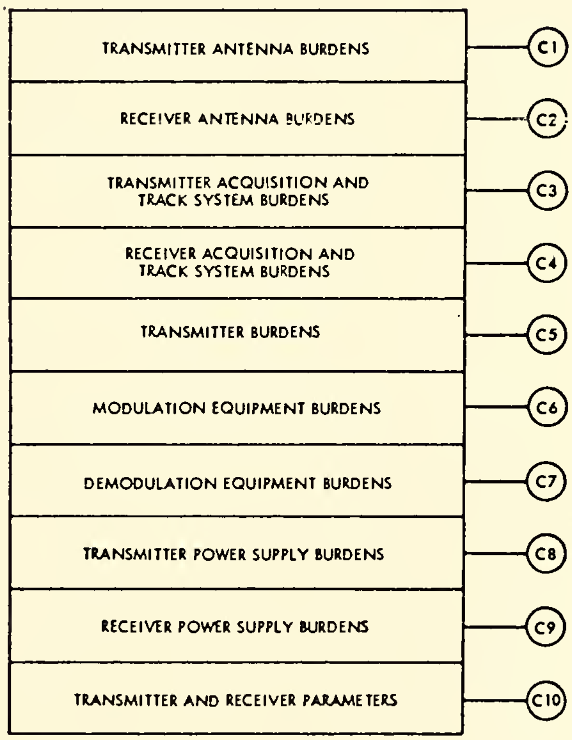

Figure A-2. Communication components analysis flow chart.

by examples of the optimization procedure. The section concludes with a design methodology which summarizes the results of the optimization methodology for optical and radio systems, and presents short cut methods of evaluating systems.

A.2 COMMUNICATION COMPONENTS ANALYSIS

The communication components analysis task is illustrated by the flow chart of Figure A-2. For each component the weight, fabrication cost, power requirement, and power dissipation are derived as a function of the system parameters. A total component cost is developed as the sum of the fabrication cost and cost of placing the component weight aboard a spacecraft, if applicable.

C1 Transmitter Antenna Burdens

The weight and fabrication cost of a transmitter antenna are proportional to the transmitter aperture diameter. The transmitter antenna weight is

$$\boxed{W_{d_T} = K_{d_T} (d_T)^{n_T} + W_{KT}}$$

and the fabrication cost is

$$\boxed{C_{\theta_T} = K_{\theta_T} (d_T)^{m_T} + C_{KT}}$$

where

d_T = transmitter aperture diameter

K_{d_T} = constant relating transmitter antenna weight to transmitter aperture diameter

K_{θ_T} = constant relating transmitter antenna fabrication cost to transmitter aperture diameter

W_{KT} = transmitter antenna weight independent of transmitter aperture diameter

C_{KT} = transmitter antenna fabrication cost independent of transmitter aperture diameter

n_T = constant

m_T = constant

The total cost associated with the transmitter antenna is the fabrication cost and the cost of placing the weight W_{d_T} aboard a spacecraft. Thus,

$$\boxed{C_{d_T} = K_{\theta_T} (d_T)^{m_T} + K_S K_{d_T} (d_T)^{n_T} + C_{KT} + K_S W_{KT}}$$

where

K_S = cost per unit weight for spaceborne equipment

C2 Receiver Antenna Burdens

The weight and fabrication cost of a receiver antenna are proportional to the receiver aperture diameter. The receiver antenna weight is

$$\boxed{W_{d_R} = K_{d_R} \, (d_R)^{n_R} + W_{KR}}$$

and the fabrication cost is

$$\boxed{C_{\theta_R} = K_{\theta_R} \, (d_R)^{m_R} + C_{KR}}$$

where

d_R = receiver aperture diameter

K_{d_R} = constant relating receiver antenna weight to receiver aperture diameter

K_{θ_R} = constant relating receiver antenna fabrication cost to receiver aperture diameter

W_{KR} = receiver antenna weight independent of receiver aperture diameter

C_{KR} = receiver antenna fabrication cost independent of receiver aperture diameter

n_R = constant

m_R = constant

The total cost associated with the receiver antenna is the fabrication cost and the cost of placing the weight W_{d_R} aboard a spacecraft. For optical systems there is an additional

fabrication cost due to fabrication of a high quality short focal length aperture when the receiver field of view is much larger than the diffraction limit, but this additional cost is usually negligible with respect to the aperture diameter dependent cost. The total receiver antenna cost is then

$$\boxed{C_{d_R} = K_{\theta_R} (d_R)^{m_R} + K_S K_{d_R} (d_R)^{n_R} + C_{KR} + K_S W_{KR}}$$

C3 <u>Transmitter Acquisition and Track System Burdens</u>

The transmitter must illuminate the receiver under fixed acquisition time limits and then maintain an angular tracking accuracy. Acquisition and tracking equipment consists of a gimbal system to slew the transmitter antenna to the desired pointing angle, a sensor to detect the line of sight rotational error between the transmitter and receiver by monitoring a communication or beacon signal emitted from the receiving site, and a stable platform reference for the sensor. The acquisition and tracking sensor signal may be obtained from 1) a secondary antenna, 2) the transmitter antenna acting as a receiving antenna on a shared basis, or 3) the antenna of a communications receiver if available at the transmitter. A beacon at the transmitter used by the receiver for its acquisition and tracking function will not affect the system parameters optimization since the beacon burdens are independent of the system parameters. Beacon burdens are considered as part of

the fixed burdens associated with the spacecraft transmitter acquisition and track system.

The weight and fabrication cost of the acquisition equipment is relatively independent of the transmitter beamwidth.

The weight of the transmitter acquisition and track system is relatively insensitive to the tracking accuracy and depends primarily upon the weight of the transmitter antenna and the weight of the transmitter sensor, stabilization, and acquisition systems. The weight of the transmitter acquisition and track system is

$$W_{QT} = W_{BT} + K_{W_{AT}} W_{d_T}$$

or

$$\boxed{W_{QT} = W_{BT} + K_{W_{AT}} K_{d_T} (d_T)^{n_T}}$$

where

W_{BT} = transmitter acquisition and track equipment and beacon system weight independent of transmitter beamwidth

$K_{W_{AT}}$ = constant relating transmitter tracking equipment weight to transmitter antenna weight

W_{d_T} = transmitter antenna weight

The tracking accuracy requirement may be stated as some fixed percentage of the transmitter beamwidth. The fabrication cost of the tracking equipment is inversely proportional

to the tracking accuracy, and hence, to the inverse of the transmitter beamwidth. Since the transmitter is diffraction limited, ($\theta_T \approx \lambda/d_T$), the fabrication cost of the transmitter tracking equipment is proportional to the transmitter aperture diameter.

The total fabrication cost of the transmitter acquisition and track system is then

$$C_{NT} = C_{AT} + K_{AT}\,(\theta_T)^{-q_T}$$

or

$$\boxed{C_{NT} = C_{AT} + \frac{K_{AT}}{(\lambda)^{q_T}}\,(d_T)^{q_T}}$$

where

λ = transmission wavelength

C_{AT} = transmitter acquisition and track equipment and beacon system fabrication cost independent of transmitter beamwidth

K_{AT} = constant relating transmitter tracking equipment fabrication cost to transmitter beamwidth

θ_T = transmitter beamwidth

q_T = constant

The total cost associated with the transmitter acquisition and track system is

$$\boxed{C_{QT} = C_{AT} + \frac{K_{AT}}{(\lambda)^{q_T}} (d_T)^{q_T} + K_S \left[W_{BT} + K_{W_{AT}} K_{d_T} (d_T)^{n_T} \right]}$$

The power requirement of the transmitter acquisition and track equipment is directly proportional to the weight of the acquisition and track system.* Thus,

$$\boxed{P_{QT} = K_{P_{QT}} \left[W_{BT} + K_{W_{AT}} K_{d_T} (d_T)^{n_T} \right]}$$

where

$K_{P_{QT}}$ = constant relating transmitter acquisition and track equipment power requirement to equipment weight

C4 Receiver Acquisition and Track System Burdens

The receiver must locate the transmitter in its field of view and then maintain an angular tracking accuracy. The implementation of the receiver acquisition and track system is the same as the transmitter acquisition and track system.

The weight and fabrication cost of the acquisition equipment is relatively independent of the receiver field of view. The weight of the receiver tracker is relatively insensitive to the tracking accuracy, and depends primarily on the weight of the receiver antenna and the weight of the receiver sensor, stabilization, and acquisition systems. The weight of the receiver acquisition and tracking systems is

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* This assumption is not strictly applicable to all tracking systems and will be examined in subsequent reports.

$$W_{QR} = W_{BR} + K_{W_{AR}} W_{d_R}$$

or

$$\boxed{W_{QR} = W_{BR} + K_{W_{AR}} K_{d_R} (d_R)^{n_R}}$$

where

W_{BR} = receiver acquisition and track equipment and beacon system weight independent of receiver field of view.

$K_{W_{AR}}$ = constant relating receiver tracking equipment weight to receiver antenna weight

W_{d_R} = receiver antenna weight

The tracking accuracy requirement may be stated as some fixed percentage of the receiver field of view. The fabrication cost of the tracking equipment is inversely proportional to the tracking accuracy, and hence to the inverse of receiver field of view. The total fabrication cost of the receiver acquisition and track system is then

$$\boxed{C_{NR} = C_{AR} + K_{AR} (\theta_R)^{-q_R}}$$

where

C_{AR} = receiver acquisition and track equipment and beacon system fabrication cost independent of receiver field of view

K_{AR} = constant relating receiver tracking equipment fabrication cost to receiver field of view

q_R = constant

θ_R = receiver field of view

The total cost associated with the receiver acquisition and track system is

$$\boxed{C_{QR} = C_{AR} + K_{AR} (\theta_R)^{-q_R} + K_S \left[W_{BR} + K_{W_{AR}} K_{d_R} (d_R)^{n_R}\right]}$$

The power requirement of the receiver acquisition and track equipment is directly proportional to the weight of the acquisition and track system.* Thus,

$$\boxed{P_{QR} = K_{P_{QR}} \left[W_{BR} + K_{W_{AR}} K_{d_R} (d_R)^{n_R}\right]}$$

where

$K_{P_{QR}}$ = constant relating receiver acquisition and track equipment power requirement to equipment weight

C5 Transmitter Burdens

The weight and fabrication cost of radio transmitters are proportional to the transmitter output power. Laser transmitters are available only at discrete wavelengths, and each laser is capable of operation over only a restricted range of output power by increasing the laser pumping power; however, at each wavelength within limits the laser weight and

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* This assumption is not strictly applicable to all tracking systems and will be examined in subsequent reports.

fabrication cost are proportional to the laser output power. Thus, the transmitter weight is

$$\boxed{W_T = K_{WT} (P_T)^{h_T} + W_{KP}}$$

and the fabrication cost is

$$\boxed{C_{FL} = K_{PT} (P_T)^{g_T} + C_{KP}}$$

where

P_T = transmitter power

K_{WT} = constant relating transmitter weight to transmitter power

K_{PT} = constant relating transmitter fabrication cost to transmitter power

W_{KP} = transmitter weight independent of transmitter power

C_{KP} = transmitter fabrication cost independent of transmitter power

h_T = constant

g_T = constant

A heat exchanger may be required for the transmitter. The fabrication cost and weight of the heat exchanger are proportional to the power dissipated by the transmitter. The heat exchanger weight is

$$\boxed{W_H = K_X \left(\frac{1-k_e}{k_e}\right) P_T + W_{KH}}$$

and the heat exchanger fabrication cost is

$$\boxed{C_H = K_H\left(\frac{1-k_e}{k_e}\right)P_T + C_{KH}}$$

where

W_{KH} = transmitter heat exchanger weight independent of transmitter

C_{KH} = transmitter heat exchanger fabrication cost independent of transmitter power dissipation

K_X = constant relating transmitter heat exchanger weight to transmitter power dissipation

K_H = constant relating transmitter heat exchanger fabrication cost to transmitter power dissipation

k_e = transmitter power efficiency, from the prime power source to the output power

The total transmitter cost is then the fabrication costs of the transmitter and associated heat exchanger and the cost of placing these units aboard a spacecraft. Thus,

$$\boxed{\begin{aligned} C_{P_T} = {} & K_{P_T} (P_T)^{g_T} + K_S K_{W_T} (P_T)^{h_T} + K_H\left(\frac{1-k_e}{k_e}\right)P_T \\ & + K_S K_X \left(\frac{1-k_e}{k_e}\right) P_T + C_{KP} + C_{KH} \\ & + K_S W_{KP} + K_S W_{KH} \end{aligned}}$$

The transmitter power requirement is

$$\boxed{P_{PT} = \frac{1}{k_e} P_T}$$

C6 Modulation Equipment Burdens

For each type of modulation, the modulation equipment weight and fabrication cost are proportional to the information rate. The modulation equipment weight is

$$\boxed{W_M = K_M R_B + W_{KM}}$$

and the modulation equipment fabrication cost is

$$\boxed{C_{FM} = K_{FM} R_B + C_{KM}}$$

where

R_B = information rate

K_M = constant relating modulation equipment weight to information rate.

K_{FM} = constant relating modulation equipment fabrication cost to information rate

W_{KM} = modulation equipment weight independent of information rate

C_{KM} = modulation equipment fabrication cost independent of information rate

The total cost associated with the modulation equipment is the fabrication cost and the cost of placing the equipment aboard a spacecraft. Thus,

$$\boxed{C_M = K_{FM}R_B + C_{KM} + K_S K_M R_B + K_S W_{KM}}$$

The power requirement of the modulation equipment is proportional to its weight. Thus,

$$\boxed{P_M = K_{P_M} K_M R_B + K_{P_M} W_{KM}}$$

where

K_{P_M} = constant relating modulation equipment power requirement to equipment weight

The modulation equipment burdens include coder burdens.

C7 Demodulation Equipment Burdens

The demodulation equipment consists of a carrier receiver followed by a subcarrier receiver, if necessary. Also included in the demodulation equipment is any cooling equipment required to lower the receiver temperature to reduce dark current and thermal noise. For each type of demodulation system the equipment weight is proportional to the information rate. The demodulation equipment weight is

$$\boxed{W_D = K_D R_B + W_{KD}}$$

and the demodulation equipment fabrication cost is

$$\boxed{C_{FD} = K_{FD} R_B + C_{KD}}$$

where

K_D = constant relating demodulation equipment weight to information rate

K_{FD} = constant relating demodulation equipment fabrication cost to information rate

W_{KD} = demodulation equipment weight independent of information rate

C_{KD} = demodulation equipment fabrication cost independent of information rate

The total cost associated with the demodulation equipment is the fabrication cost and the cost of placing the equipment aboard a spacecraft. Thus,

$$\boxed{C_D = K_{FD}R_B + C_{KD} + K_S K_D R_B + K_S W_{KD}}$$

The power requirement of the demodulation equipment is proportional to its weight

$$\boxed{P_D = K_{P_D} K_D R_B + K_{P_D} W_{K_D}}$$

where

K_{P_D} = constant relating demodulation equipment power requirement to equipment weight

The demodulation equipment burdens include decoder burdens.

C8 Transmitter Power Supply Burdens

The input power requirement of the transmitter specifies the power requirement for the transmitter power supply. The power supply is defined here to include the power source plus voltage or current conversion equipment. The power

supply weight and fabrication cost are proportional to the power requirement. The transmitter power supply weight is

$$W_{ST} = K_{W_{ST}} P_{ST} + W_{KE}$$

and the fabrication cost is

$$C_{FT} = K_{ST} P_{ST} + C_{KE}$$

where

W_{KE} = transmitter power supply weight independent of transmitter power requirement

C_{KE} = transmitter power supply fabrication cost independent of transmitter power requirement

P_{ST} = transmitter power supply power requirement

$K_{W_{ST}}$ = constant relating transmitter power supply weight to power requirement

K_{ST} = constant relating transmitter power supply fabrication cost to power requirement

The transmitter power supply power requirement is

$$P_{ST} = P_M + P_{PT} + P_{QT}$$

where

$P_M = K_{P_M} K_M R_B + K_{P_M} W_{KM}$ = modulation equipment power

$P_{PT} = \dfrac{P_T}{k_e}$ = transmitter power requirement from the prime power source

$P_{QT} = K_{P_{QT}} \left[W_{ST} + K_{W_{AT}} K_{d_T} (d_T)^{n_T} \right]$ = transmitter acquisition and tracking equipment power requirement

The transmitter power supply weight is then

$$\boxed{\begin{aligned} W_{ST} = K_{W_{ST}} \Bigg\{ & K_{P_M} K_M R_B + K_{P_M} W_{KM} + \frac{P_T}{k_e} \\ & + K_{P_{QT}} \left[W_{BT} + K_{W_{AT}} K_{d_T} (d_T)^{n_T} \right] \Bigg\} + W_{KE} \end{aligned}}$$

The total cost associated with the transmitter power supply is the transmitter power supply fabrication cost plus the cost of placing the equipment weight aboard a spacecraft. Thus,

$$\boxed{\begin{aligned} C_{ST} = \left[K_{ST} + K_S K_{W_{ST}} \right] \Bigg\{ & K_{P_M} K_M R_B + K_{P_M} W_{KM} + \frac{P_T}{k_e} \\ & + K_{P_{QT}} \left[W_{BT} + K_{W_{AT}} K_{d_T} (d_T)^{n_T} \right] \Bigg\} + K_S W_{KE} + C_{KE} \end{aligned}}$$

C9 Receiver Power Supply Burdens

The input power requirements of the receiver specify the power requirement for the receiver power supply. The power supply weight and fabrication cost are proportional to the power requirement.

The receiver power supply weight is

$$W_{SR} = K_{W_{SR}} P_{SR} + W_{KF}$$

and the fabrication cost is

$$C_{FR} + K_{SR} P_{SR} + C_{KF}$$

where

W_{KF} = receiver power supply weight independent of receiver power requirement

C_{KF} = receiver power supply fabrication cost independent of receiver power requirement

P_{SR} = receiver power supply power requirement

$K_{W_{SR}}$ = constant relating receiver power supply weight to power requirement

K_{SR} = constant relating receiver power supply fabrication cost to power requirement

The receiver power supply power requirement is

$$P_{SR} = P_D + P_{QR}$$

where

$P_D = K_{P_D} K_D R_B + K_{P_D} W_{KD}$ = demodulation equipment power requirement

$P_{QR} = K_{P_{QR}} \left[W_{BR} + K_{W_{AR}} K_{d_R} (d_R)^{n_R} \right]$ = receiver acquisition and tracking equipment power requirement

The receiver power supply weight is then

$$\boxed{W_{SR} = K_{W_{SR}} \left\{ K_{P_D} K_D R_B + K_{P_D} W_{KD} + K_{P_{QR}} \left[W_{BR} + K_{W_{AR}} K_{d_R} (d_R)^{n_R} \right] \right\} + W_{KF}}$$

The total cost associated with the receiver power supply is the receiver power supply fabrication cost plus the cost of placing the equipment aboard a spacecraft. Thus,

$$C_{SR} = \left[K_{SR} + K_S K_{W_{SR}}\right] \Big\{ K_{P_D} K_D R_B + K_{P_D} W_{KD} + K_{P_{QR}} \left[W_{BR} + K_{W_{AR}} K_{d_R} (d_R)^{n_R}\right] \Big\} + C_{KF}$$

C10 Transmitter and Receiver Parameters

The transmitter and receiver of an optical communication system are characterized by the following parameters:

η = quantum efficiency

I_d = dark current

G = photo detector gain

R_L = receiver load resistance

P_O = local oscillator power

B_i = optical input filter bandwidth

B_o = receiver output filter bandwidth

τ_t = transmitter transmissivity

τ_r = receiver transmissivity

TABLE A-1 [Refs. 34 and 35]

COMPONENT BURDEN RELATIONS

COMPONENT	CONSTANT	UNITS	VALUE
TRANSMITTER ANTENNA			
$W_{d_T} = K_{d_T}(d_T)^{n_T} + W_{KT}$	K_{d_T}	lb/cm^2	0.0303
	n_T	-	2.2
$C_{\theta_T} = K_{\theta_T}(d_T)^{m_T} + C_{KT}$			
$C_{d_T} = C_{\theta_T} + K_s(W_{d_T})$	W_{KT}	lb	25
	K_{θ_T}	$\$/cm^2$	72
	m_T	-	2
	C_{KT}	\$	40×10^3
	K_s	\$	10×10^3
ACQ. AND TRACKING SYSTEM			
$W_{QT} = W_{BT} + K_{W_{AT}} W_{d_T}$	W_{BT}	lb	40
$C_{NT} = C_{AT} + K_{AT}(\theta_T)^{-q_T}$	$K_{W_{AT}}$	lb/lb	0.13
$P_{QT} = K_{P_{QT}}(W_{QT})$	C_{AT}	\$	4×10^5
$C_{QT} = C_{NT} + K_s(W_{QT})$	K_{AT}	$\$/(\text{radian})^{q_T}$	1.1×10^4
	q_T	—	0.3
	$K_{P_{QT}}$	watts/lb	0.48

TABLE A-1 (Continued)

COMPONENT	CONSTANT	UNITS	VALUE
TRANSMITTER			
$W_T = K_{WT}(P_T)^{h_T} + W_{KP}$	K_{WT}	lb/watt	2
$C_{FL} = K_{PT}(P_T)^{g_T} + C_{KP}$	h_T	-	1
$P_{PT} = \frac{1}{k_e} P_T$	W_{KP}	lb	25
$C_{P_T} = C_{FL} + K_s(W_T)$	K_{PT}	$/watt	1.43
	g_T	-	1
	C_{KP}	$	10×10^3
	k_e	%	10
MODULATION EQUIPMENT			
$W_M = K_M R_B + W_{KM}$	K_M	lb/bit	3×10^{-7}
$C_{FM} = K_{FM} R_B + C_{KM}$	R_B	bits	3×10^7
$P_M = K_{P_M}(W_M)$	W_{KM}	lb	10
$C_M = C_{FM} + K_s(W_M)$	K_{FM}	$/bit	5×10^{-4}
	C_{KM}	$	15×10^3
	K_{P_M}	watts/lb	5

TABLE A-1 (Continued)

COMPONENT	CONSTANT	UNITS	VALUE
DEMODULATOR EQUIPMENT			
$W_D = K_D(R_B) + W_{KD}$	K_D	lb/bit	2×10^{-7}
$C_{FD} = K_{FD}(R_B) + C_{KD}$	W_{KD}	lb	55
$P_D = K_{P_D}(W_D)$	K_{FD}	\$/bit	1×10^{-4}
$C_D = C_{FD} + K_s(W_D)$	C_{KD}	\$	27.5×10^{3}
	K_{P_D}	watts/lb	3.33
XMTR POWER SUPPLY			
$W_{ST} = K_{W_{ST}} P_{ST} + W_{KE}$	$K_{W_{ST}}$	lb/watt	5×10^{-2}
$C_{FT} = K_{ST}(P_{ST}) + C_{KE}$	W_{KE}	lb	0
$P_{ST} = P_M + P_{PT} + P_{QT}$	C_{KE}	\$	0
	K_{ST}	\$/watt	53
RCVR POWER SUPPLY			
$W_{SR} = K_{W_{SR}} P_{SR} + W_{KF}$	$K_{W_{SR}}$	lb/watt	5×10^{-2}
$C_{FR} = K_{SR}(P_{SR}) + C_{KF}$	W_{KF}	lb	0
$P_{SR} = P_D$	C_{KF}	\$	0
	K_{SR}	\$/watt	53

TABLE A-1 (Concluded)

COMPONENT	CONSTANT	UNITS	VALUE
HEAT REJECTION			
$W_H = K_X(1-k_e/k_e)P_T + W_{KH}$	W_{KH}	lb	0
$C_H = C_{KH} + K_H(1-k_e/k_e)P_T$	C_{KH}	\$	13.8×10^3
	K_H	\$/watt	1.97
	K_X	lb/watt	2.5×10^{-2}

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